IMPACTS OF VESSEL NOISE PERTURBATIONS ON THE RESIDENT SPERM WHALE POPULATION IN THE GULF OF MEXICO

A Dissertation

by

ALYSON JULIE AZZARA

Submitted to the Office of Graduate Studies of Texas A&M University
and the Graduate Faculty of The Texas A&M University - Corpus Christi
in partial fulfillment of the requirements for the joint degree of

DOCTOR OF PHILOSOPHY

May 2012

Major Subject: Marine Biology

Impacts of Vessel Noise Perturbations on the Resident Sperm Whale Population in the Gulf of Mexico

IMPACTS OF VESSEL NOISE PERTURBATIONS ON THE RESIDENT SPERM WHALE POPULATION IN THE GULF OF MEXICO

A Dissertation

by

ALYSON JULIE AZZARA

Submitted to the Office of Graduate Studies of Texas A&M University
and the Graduate Faculty of The Texas A&M University - Corpus Christi
in partial fulfillment of the requirements for the joint degree of

DOCTOR OF PHILOSOPHY

Approved by:

Chair of Committee,	Wyndylyn von Zharen
Committee Members,	Bernd Würsig
	Tarla Peterson
	Robert Randall
Interdisciplinary Faculty Chair,	Gilbert Rowe

May 2012

Major Subject: Marine Biology

ABSTRACT

Impacts of Vessel Noise Perturbations on the Resident Sperm Whale Population in the Gulf of Mexico.

(May 2012)

Alyson Julie Azzara, B.A., Temple University;
M.S., Texas A&M University
Chair of Advisory Committee: Dr. Wyndylyn von Zharen

The Gulf of Mexico is home to two of the world's ten busiest ports by cargo volume, the Port of New Orleans and the Port of Houston; and in 2008, these ports hosted a combined 14,000 ships, a number which is likely only to increase. Past research shows that this increase in shipping worldwide has historically lead to an increase in ambient noise level of 3-5dB per decade. Sperm whales in the Gulf of Mexico are considered a genetically distinct, resident population. They have a preference for the Louisiana-Mississippi Shelf region which directly overlaps with the entrance to the Mississippi and the Port of New Orleans. Disruptions from vessel noise could influence feeding and breeding patterns essential to the health of the stock. Data used in this analysis were collected continuously over 36 days in the summer of 2001 from bottom moored Navy Environmental Acoustic Recording System (EARS) buoys. Results showed a significant difference ($P<0.05$) in noise level between hours with ships passing and hours without.

Metrics for 56 ship passages were analyzed to compare duration of ship passage with duration of maximum received level (MRL) during ship passage. Results of that analysis showed an average ship passage of 29 minutes with average MRL lasting 23% of the ship passage and an average increase of 40dB. Lastly, click counts were made with the Pamguard. Click counts for ship passages were completed for 35 min and 17.5 min before and after the estimated closest point of approach (CPA) for each ship. Results showed a 36% decrease in the number of detectable clicks as a ship approaches when comparing clicks detected at intervals of both 35 minutes before and 17 minutes before the CPA; additionally, 22% fewer clicks were counted 30 min after the ship than 30 min before (results significant at the P=0.01 level). These results indicate a potential change in sperm whale behavior when exposed to large class size vessel traffic (e.g. tankers and container ships) from major shipping lanes. Recommendations for addressing this issue are discussed.

DEDICATION

This dissertation is dedicated to: Bella, Mato, Mia, Penny, Minnie, Midnight, Red, Suzie Q, College, Skipper, Prince Charming, Rigs, Dash, Hopper, and Athena, whose daily love and humor kept it all in perspective.

ACKNOWLEDGEMENTS

There are many people who were instrumental in the completion of this dissertation. First and foremost I want to express my gratitude to my committee chair, Dr. von Zharen who has supported my efforts to combine science and management. I could not have achieved success without her guidance, teaching, and patience. My committee members, Dr. Würsig, Dr. Peterson, and Dr. Randall, with their individual expertise and guidance, helped expand my research to create a truly interdisciplinary project. This dissertation would not be half of what it is without their help, and I thank them whole-heartedly.

This dissertation has truly been a united effort with the support from multiple institutions. Dr. Lohrenz and Dr. Caruthers from the University of Southern Mississippi started me on the path to my PhD and provided data support and connections for the continuation of the research at Texas A&M University at Galveston. Dr. Ioup and his fellow researchers at the University of New Orleans gave me access to the buoy data and their processing programs; Joal Newcomb from the Office of Naval Research was absolutely amazing with his assistance editing programs and processing data. His assistance with the research and analysis was unparalleled and I absolutely could not have done it without him. I would also like to thank Dr. Doug Gillespie and Dr. Dave Mellinger for their help with the click counts and sperm whale click analysis. The time and instruction they provided made the difference between thinking I knew what I was doing and actually knowing what I was doing. For their help with the amazing maps, Kyle Ward and Brendan Hurley; the dissertation was great, but those maps really made the difference, and I am so grateful that you were willing to work with me, Kyle, to provide the data, and Brendan, to create the maps.

As with any project, those who funded me, made the work possible so, I would also like to thank the University of Southern Mississippi, Department of Marine Science; Texas A&M University at Galveston (TAMUG), Department of Marine Science; TAMUG Research Office; the Marine Technology Society; Texas Sea Grant; Erma Lee and Luke Mooney; and the TAMUG Graduate Student Society.

As with any great personal accomplishment, there are a number of people who have stood behind me and supported me every day, never letting me give up: Michelle Cortez, Sarah Orlando, Julia O'Hern, Jennie Greytak, Mtihriel Mackay, Sarah Piwetz, Courtney Smith, Allie Mojzis; and, of course, my family: Mom, Dad, Nana, Popie, Mal and Sid, and all the rest who have told me to relax on a regular basis and celebrated with me through every milestone, big or small, THANK YOU.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION AND BACKGROUND

General Introduction

The Gulf of Mexico (GoM) is a center of marine activities, from seismic exploration to shipping, drilling, platform installation, lightering, and construction, among others. It is home to two of the world's ten busiest ports by cargo volume, the Port of New Orleans and the Port of Houston; and in 2008, these ports hosted a combined 14,000 ships (approximately 6,000 vessel calls were recorded at the Port of New Orleans and 8,000 vessel calls at the Port of Houston [Port Authority of Houston, 2009; Port Authority of New Orleans, 2009]), a number which is likely only to increase (Macdonald et al., 2006). Past research shows that this increase in shipping worldwide has historically lead to an increase in ambient noise level of 3-5dB per decade (Andrew et al., 2002). The noise from these vessels is continuous and may be a significant source of stress for animals in the marine environment. This is of particular concern for the resident sperm whale population in the GoM because they are most abundant on the Louisiana-Mississippi shelf and in the direct path of a number of converging shipping lanes. They are also an endangered species.

This issue of overlap between commercial and ecological use is not limited to the New

---

This dissertation follows the style of the *Journal of the Acoustical Society of America.*

Orleans Ship Channel or to the GoM. This is an issue faced by any shipping port where marine mammals are found in close proximity to vessel traffic. Examples of this in the U.S. are ports in Boston, Washington, California, New York, New Jersey, and many others along the eastern and western seaboards. According to the National Oceanic and Atmospheric Association's (NOAA) National Marine Fisheries Service (NMFS), there are 21 marine mammal species protected under the endangered species act and 2 additional species protected under U.S Fish and Wildlife Service (Manatees and Sea Otters) (NOAA Office of Protected Resources) that inhabit port associated waters. There are a total of 120 marine mammal species globally which are likely to be affected by vessel traffic (Perrin et al., 2008).

Sperm whales are federally protected by both the Marine Mammal Protection Act (MMPA) and the Endangered Species Act (ESA). Under these laws, it is illegal to harm marine mammals in U.S. waters. Harm is defined by the ESA to include any action that causes behavioral changes of marine mammals or any type of harassment such as close approach by vessels (Würsig et al., 2000). Until recently, anthropogenic noise had not been considered a major factor for behavioral changes. It is now recognized to be dangerous and sometimes fatal for marine mammals in close proximity to noise sources (Jasny et al., 2005). Thus, it is imperative that new attention be given to the effects of chronic noise exposure, especially in an area as heavily trafficked as the GoM as well as all port areas with a marine mammal presence.

Physical Forcing in the GoM

Physical ocean processes are strongly linked with biological processes. In order to understand where a population of whales is located, or why prey aggregate in a certain area, the physical environment must be understood. The GoM is a dynamic environment with several major forces dictating physical processes. The most prominent is the Loop Current, which is a precursor of the Gulf Stream that enters through the Yucatan Channel and exits through the Florida Straits. When the Loop Current extends very far north or northwest, large scale (~200 km) anti-cyclonic eddies separate from the Loop Current and propagate west or southwest through the GoM (Hamilton, 1992). The dominant dynamic mechanism controlling the separation of Loop Current eddies from the Loop Current is instability within the Loop Current produced by horizontal sheer from the natural tendency of the water masses to propagate west with the Coriolis force and not to the east and out the Florida Straits (Sturges and Leben, 2000). Additionally, variation in the flow through the Yucatan Channel influences the strength and extension of the Loop Current to the northwest, which also affects the frequency of Loop Current eddy detachment (Leben, 2005).

Eddies in the GoM typically extend downward from the surface to depths of 500 to 600 meters. Anti-cyclonic loop current eddies are all associated with deep anti-cyclone-cyclone pairs. These deep pairs are guided by bottom bathymetry as they migrate westward. Because the lower deep anticyclone decays more rapidly, surface eddies are often found further west and without their deeper counterpart (Welsh and Inoue, 2000).

Eddies can interact with the Loop Current, deep bathymetry, and other Loop Current eddies. These secondary eddy interactions are often the main forcing factors along the shelf-edge and may influence the circulation of shallower continental shelf waters (Hamilton, 1992).

Sperm Whale Habitat

In the GoM, the 15 degree temperature mark is the strongest delineation for female and juvenile sperm whale habitat. While males move freely about the oceans to the edge of the ice pack, females and juveniles remain along the edge of these temperature boundaries. Depth is another separating factor; females rarely enter the waters above the continental shelf (Caldwell et al., 1966; Whitehead, 2003) and are mostly found between the 800m and 1200m isobaths (Mullin et al., 1994; Mullin and Hansen., 1999). The preferred grounds are areas of high primary and secondary productivity (Gulland, 1974; Jacquet and Whitehead, 1996; Jaquet et al., 1996). Over small scales of kilometers to hundreds of kilometers, sperm whales are associated with strong oceanographic features such as continental shelf breaks (Waring et al., 2001, Davis and Fargion, 1996; Davis et al., 1998), cyclonic eddies (Biggs et al., 2000), and warm core rings breaking off from the Gulf Stream (Waring et al., 1993; Griffen, 1999) because sperm whale prey concentrate along the boundaries of these features (Whitehead 2003).

In the GoM, the Mississippi River injects nutrients into an otherwise oligotrophic region (Baumgartner et al., 1999). The Mississippi River is the largest river system in North

America with a drainage basin that includes 43% of U.S. interior and parts of Canada. The river discharges an average of $1.83x10^4$ km^3 of freshwater per year into the GoM creating a plume detectible up to 100km offshore (Grimes, 2001).

As surface waters converge, planktonic organisms accumulate at the surface; this contributes to the higher concentrations of planktonic organisms at frontal boundaries like those existing on the Mississippi Shelf. For some taxa and size classes, feeding in these areas is advantageous (Grimes, 2001). Hopkins (1982) investigated taxonomic composition of zooplankton available for higher trophic levels and found a higher standing stock in waters adjacent to the loop current.

In the northern GoM, wind driven upwelling and epipelagic nutrient enhancement from riverine surface flow from the Mississippi, as well as interaction with eddies may also contribute to enhanced nutrient availability and primary production (Riley, 1937; Lohrenz et al., 1990; Grimes and Finucane, 1991; Lohrenz et al., 1999; Wiseman and Sturges, 1999; Biggs and Ressler, 2001). The doming of cyclonic eddies is linked with increased primary production, and if these types of systems persist, can fuel increases in plankton stocks (Ressler and Jochens, 2003) which may increase feeding opportunities, making them preferable habitats for sperm whales. Biggs et al. (2005) found that at times with current flow onto the shelf, on-margin, into the Mississippi canyon, sperm whales were rarely seen. Conversely, times of along-margin and off margin flow periods were correlated with high sperm whale presence. Most sperm whales were encountered in areas of negatives sea surface height or higher than average surface chlorophyll concentration which is often found along the frontal boundaries discussed. This preference is apparent in sperm whale distribution observed by Biggs et al. (2000) and Davis et al. (2000) (Wormuth et al., 2000).

These preferences are supported by survey distribution data on sperm whales and other marine mammals in the GoM. Davis et al. (2002) found that cetacean concentrations along the shelf increased in the presence of cyclonic eddy systems which correlate with increases in nutrients and primary productivity. This area along the mouth of the Mississippi with increased mixing and enhanced primary and secondary production may explain the presence of sperm whales within 100km of the delta.

These trends in sperm whale congregations along the Mississippi shelf are also repeated further east around bachelor groups of adolescent sperm whales. In the summer, bachelor male groups increase more in the east than in the west. They are correlated with sea surface chlorophyll and appear geographically separated from female/juvenile groups by a strong mixing boundary offshore of the Mississippi delta region (O'Hern and Biggs, 2009). In this location, distribution is attributed to prey availability which may be connected with transport of water from the Mississippi River over the shelf where it interacts with cyclonic and anti-cyclonic eddies fostering mixing and upwelling. This increased mixing also enhances the flow of nutrient rich water into the region, creating possible areas of production over the canyon (Hamilton and Lee, 2005).

Sperm Whale Distribution

Sperm whales are distributed worldwide. They are found from the tropics to the edge of the ice at both the North and South Pole (Leatherwood and Reeves, 1983; Rice, 1989; Whitehead, 2002). Sperm whales in the GoM are considered to be a resident, genetically distinct population, separated, to an extent, from the rest of the globe's population (Mullin et al., 2003; Jaquet, 2006; Jochens et al., 2008). Comparisons of photo identification records between 285 GoM whales and 2,500 whales from the Atlantic and Mediterranean yielded no overlap in individuals. This pattern was also true for comparisons between animals in the Eastern Caribbean Sea and the GoM (Gero et al., 2007). Genetic distribution studies analyzing matrilineally inherited DNA confirm the separation between GoM populations and other ocean basins' populations; however, comparisons of biparentally inherited DNA did not show a significant difference, meaning that while the females remain separated, mature male sperm whales do, indeed, move in and out of the GoM (Engelhaupt et al., 2009).

An additional component concerning communication further supports this stock separation. Sperm whales use a series of clicks called "codas" to communicate socially. These codas can be grouped into social clans and recognized regionally (Watkins and Schevill, 1977; Whitehead and Weilgart, 1991; Rendell and Whitehead, 2001; Rendell and Whitehead, 2003). Recordings of these coda patterns were compared between GoM sperm whales and those from other regions of the Atlantic and were found to be different. This suggests that there is little cultural exchange between social groups in the

Atlantic and GoM (Gordon et al., 2008; Antunes, 2009). On average, females in the GoM are 1.5 – 2 meters smaller than whales measured in other parts of the world. In addition, group sizes for females and juveniles are also smaller, more similar to groups in the Caribbean, but between one third and one quarter the size of groups found in the Pacific (Richter et al,. 2008; Jaquet and Gendron, 2009).

Population estimates for sperm whales in the GoM are based mainly on shipboard marine mammal surveys of the northern GoM. This area is approximately 40% of the total GoM, and while surveys of the southern Bay of Campeche are not regularly undertaken, stranding and sighting reports confirm the presence of whales in this area. These data are supported by tagging data from the 2004/2005 field season of the Sperm Whale Seismic Study (SWSS) and by logbook records from whalers in the GoM over 100 years ago. Maps of the sightings and tags overlap nicely showing continuity of habitat use over large time scales (Jochens et al., 2008).

Longevity and Life History

In order to better understand distribution and large scale social organization, this next section will briefly discuss sperm whale life history. Female sperm whales have a 15 month gestation period before giving birth. Newborn sperm whales are about 4m long and weigh approximately one ton (Best et al., 1984, Whitehead, 2003). They generally suckle for the first two years, but with great variability in length of time, and are weaned gradually although they are able to eat solid food within the first year (Best et al., 1984).

There is evidence to suggest that female groups care for sperm whale calves. Some of the evidence for group care is shown in changes in dive synchrony where females in a group will stagger their foraging dives which decreases the time a calf is alone at the surface (Whitehead, 1996). Sperm whales have very characteristic dives, typically preceded by a fluke up, and can last for 30-45 minutes on average, although some dives can last much longer. Dives are separated by 7-10 minute rests at the surface where the whales will breathe before beginning their next dive. Dive depths range from 300- 800m, although some dives are as deep as 2km. Very young sperm whales are limited to shallow dives of a few hundred meters before surfacing. Shallower dives are often made when disturbed, but these are not generally long dives and are not usually preceded by a fluke up.

Growth for male sperm whales is more rapid than for females and males can be up to 9% larger by 10 years of age. Unlike females, males leave the home group between ages 3 and 15 and are often found in bachelor groups throughout their teens and twenties (Whitehead, 2003). As they age, they move away from these social groups, migrating further from their home grounds and becoming more solitary. Although males become sexually mature in their teens, they do not appear to take part in mating until their late twenties. Females, conversely, generally stay with their home groups and become sexually mature at around 9 years of age. They can give birth approximately every 5 years which decreases over time to intervals of 15 years by the time females reach age 40 (Best et al., 1984; Rice, 1989; Whitehead, 2003). Females can live into their eighties and possibly older, but much information on longevity is still unknown. Because of their long life span and low reproductive rate, sperm whales are considered a K-selected species. This means that the majority of their population control is derived from resource competition among their con-specifics. Such species have low rates of population increase which is an important factor when a population is recovering from mass mortalities like those that result from large scale whaling (Whitehead, 2003).

Sperm Whale Recovery from Whaling

There are records of whaling in the GoM from the 1700's to early 1900's (Townsend, 1935). A recent article by Reeves et al. (2011) found the last recorded whaling voyage to the GoM took place in 1877; however, many other whaling trips were made to the Caribbean until 1923 (Townsend, 1935). Based on an assessment of logbook records and inferred information from those books, Reeves et al. (2011) estimate the total number of whales struck or taken on 204 voyages between the 1780's and 1870's to be 1,179, which they state as negatively biased based on lack of access to records. In addition, the logs showed that these whales were smaller than those caught in other regions, yielding fewer barrels of oil, on average, than in other areas. The mention of few "large whales" and the reference to "small whales" supports current research that finds that sperm whales in the GoM are smaller than in other regions. This presents an interesting insight into the distribution of whales removed from the GoM. While the number of whales is not startling when compared with the quarter million taken by the American whale fishery as a whole, when studied on the finer geographic scale of just the GoM, the number of whales taken becomes more important. When whaling began in the GoM in the 1780's, whalers were likely exploiting a nearly pristine population (Reeves et al., 2011). Unless this exploitation caused a huge shift in the composition of the population, this population has historically been comprised of females, calves, and juvenile males. Thus, the majority of the population targeted, although likely unintentionally, by this regional fishery was potentially females of reproductive age within established family groups. From what is known of sperm whale culture, subgroups (extended family groups) are important to social structure, including the raising of calves. This removal of females and long-term disruption of family structure may be a key factor in determining the recovery of the stock and its current stability.

By 1974, based on surveys of the GoM between 1950 and 1969, sperm whales were no longer considered common and thus no longer subject to commercial fishing (Lowery, 1974). A number of aerial and ship based surveys during the early 1990's were the first dedicated to marine mammal population estimation in the GoM. Based on four field seasons during the summers of 1990-1994, the estimated population for sperm whales was 530. Further surveys were conducted from 1996-2001. With the data pooled from those 2 surveys, using a newer analysis technique, the abundance estimate increased to 1,340. A later re-estimation of the 1991-1994 data using the newer analysis amended the original estimation from that time to 805 (Waring et al., 2011). Because recommendations from the Guidelines for Assessing Marine Mammal (GAMMS) Workshop Report (Wade and Angliss, 1997) suggest the exclusion of estimates older than eight years (older estimates are unreliable in this case), the most recent estimations do not include data from 1990-1994. These newest population estimations based on the surveys from 2003 and 2004 suggest an average population of 1,665, with a minimum population of 1,409 (Waring et al., 2011).

GoM Sperm Whale Distribution

Several important pieces of information can be attained from analyzing spatial distributions of sperm whales over time. Figure 1) shows the distribution of sperm whales based off of visual sightings and landed whales in the GoM from whaling vessels between the 1780’s-1870’s (Reeves et al., 2011). Data are obviously biased toward where whaling vessels frequently visited. Figure 2) is the most recent distribution map for sperm whales in the GoM from their 2010 stock assessment. While it is possible to visually detect areas with higher density, Figure 3) is a density distribution map highlighting areas of aggregations in red. From this figure, it is clear that the 1000m isobath off the Mississippi River is a hot spot for sperm whale congregation. The final figure shown here, Figure 4), is an overlay of historical whaling points (green crosses) with modern sperm whale positions (black dots). There is clear overlap with locations from whaling data showing continuity in habitat preference over several centuries. There is also a clear overlap with ship points from vessels transiting in and out of the Mississippi. These ship points and their importance will be discussed further in later chapters.

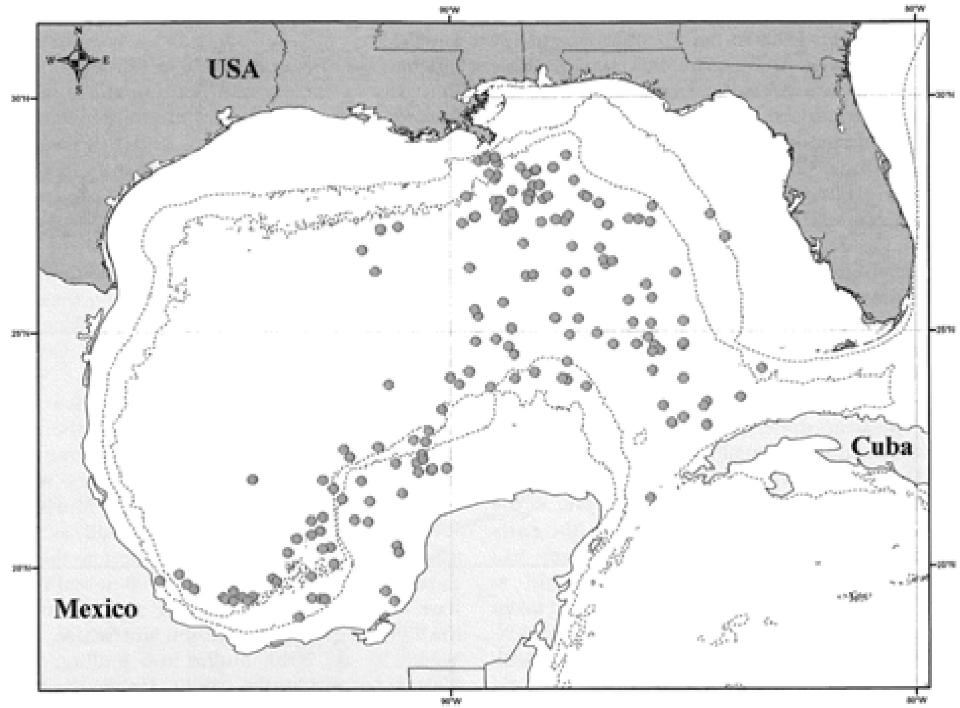


Figure 1: Distribution of sperm whales based off of visual sightings and landed whales in the GoM from whaling vessels between the 1780's-1870's (Reeves et al., 2011).

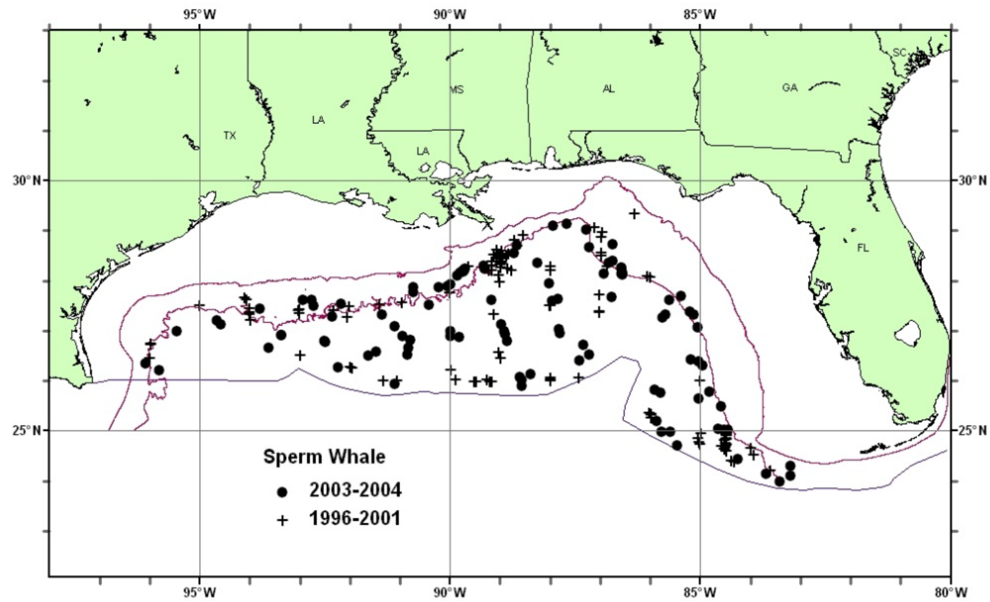


Figure 2: Distribution of sperm whales in the GoM as published by NOAA 2010 stock reports.

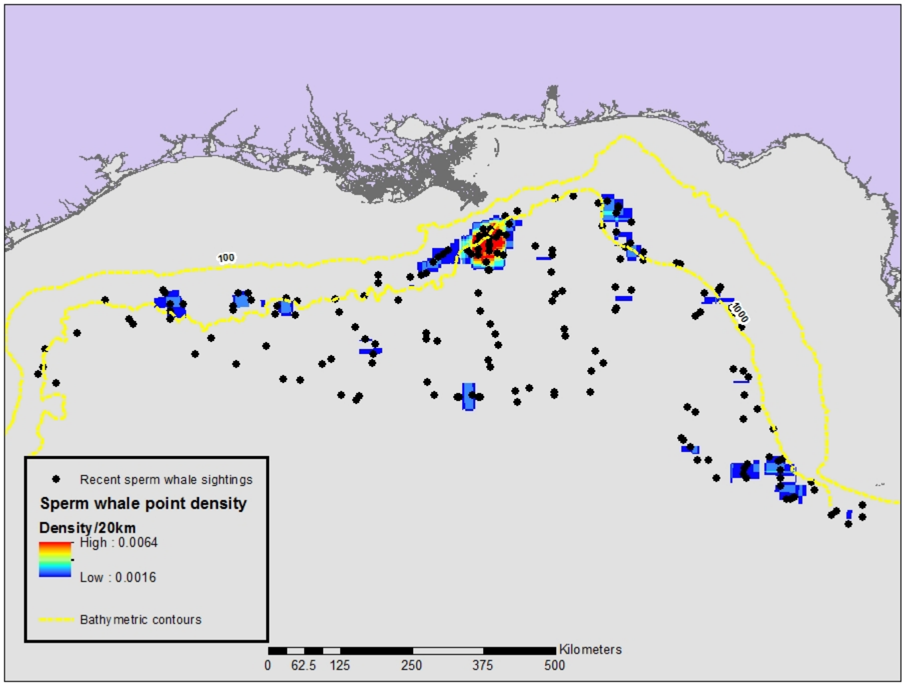


Figure 3: Displays sperm whale density data based on NOAA 2010 Stock Report. Areas with higher densities are shown in red (areas with densities less than 0.0016 shown in grey) [Map created by Brendan Hurley, GIS specialist].

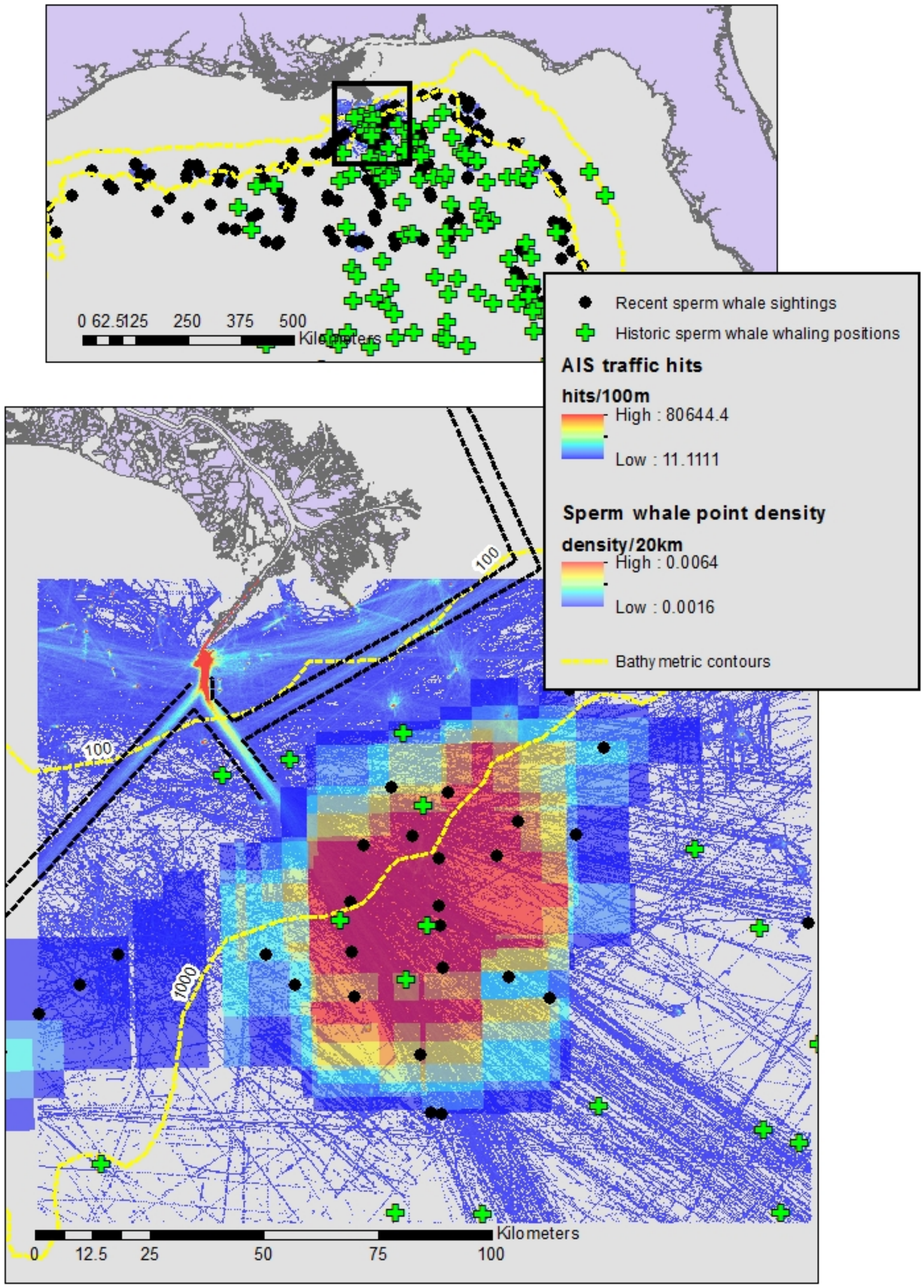


Figure 4: Overlay of current sperm whale locations (black dots) with historic locations from whaling logs (green crosses). These points are super-imposed over AIS ship track data from 2011. (AIS data provided by Kyle Ward a Physical Scientist at NOAA's Office of Coast Survey. Map created by Brendan Hurley, GIS specialist).

Noise Impacts

There is an ongoing discussion about the effects of anthropogenic noise perturbations on marine mammals, particularly on resident sperm whales in the GoM. Because of the increasing seismic exploration, increase in low frequency sonar, and vessel traffic, these and other anthropogenic contributors of noise to the marine environment are discussed. Several studies report reactions to seismic surveys where sperm whales change their vocalizations or leave the area (Bowels et al. 1994; Mate et al. 1994) [there are conflicting reports on this, with some data showing no significant change (McCall Howard 1999; Moscrop and Swift 1999)]. Whitehead (2003) discusses examples where sperm whales in small groups will avoid areas of high anthropogenic noise; however, at times where significant sources of prey resources were located within the affected area, the whales did not leave. This type of behavior may lead to increased exposure from anthropogenic noise based on of lack of avoidance. For example, in the Canary Islands, two sperm whales struck by ships were found to have significant hearing damage most likely caused by repeated exposure to anthropogenic noise (André et al., 1997). Given the large number of ships transiting the GoM and the ongoing seismic exploration, it is imperative for future management strategies to include accurate assessments of the impacts of noise pollution on sperm whales and develop a comprehensive management plan to address these impacts.

CHAPTER II

ACOUSTICS AND SPERM WHALE COMMUNICATION

Review of Acoustics as they Apply to Marine Mammals

Acoustic energy (sound) consists of molecular vibrations that travel at the speed of sound. The vibrations in the direction of propagation are longitudinal waves which consist of fluid particles vibrating. The positive peaks in energy are places where particles come together and the negative peaks are where the particles spread apart. This pattern of compression and rarefaction will move as a longitudinal wave away from the source as it transfers energy (Au and Hastings, 2008). Each sound wave can also be defined by its individual parameters: amplitude, wavelength, period, speed, and frequency. Since sound is a mechanical wave motion, it defines all motion within a compressible medium regardless of whether humans can hear it. These divisions in audibility have been defined as ultrasonic (too high for humans, >20,000Hz) and infrasonic (too low for humans < 20Hz), although the range of hearing for different marine mammals varies greatly from humans (Richardson et al., 1995).

There are several ways to measure sound. The most common measure is in pressure or micropascals (after Blaise Pascal), generally represented as µPa. One pascal is the pressure that results from the force exerted by one newton over an area of one square meter. Pascals are the “new” unit replacing the dyne/cm^2 called the microbar (1pascal =

10^{-5} microbar). Acoustic intensity is more commonly discussed but less commonly measured and is usually an inferred value. Acoustical intensity is measured in watts/m^2 and is defined as the acoustical power per unit area in the direction of propagation. This power is derived from the pressure squared and is not directly measured (Richardson et al., 1995).

The decibel is a unit that provides a convenient way of comparing acoustic quantities, usually intensity or pressure. The decibel (dB) was introduced as a compressed scale able to represent the large dynamic range humans (and now, marine mammals) experience. In addition, humans do not hear on a linear scale, rather a logarithmic one, and one decibel is approximately the smallest change in sound level detectible (Chapman and Ellis, 1998). Two important representations of acoustic energy are sound intensity level (SIL) and sound pressure level (SPL). The difference in these two values originates from the units first used to measure either pressure or intensity. Sound intensity level originates from the measurements of the intensity in watts/m^2 and is converted to dB through the equation:

Intensity level (db) = $10 \log (I/I_0)$,

where I_0 is the reference intensity, for example 1 W/m^2. Intensity is proportional to the pressure squared, so the equation for the sound pressure level is:

Sound Pressure Level (dB) = $20 \log (P/P_0)$,

where the reference pressure, $P_{0,}$ is 1 µPa (Au, 1993).

This often becomes confusing since SIL and SPL once converted to dB are often interchanged. In these cases, it is particularly important to note the reference unit so that it is understood from where those measurements come.

Reference units become more significant when referring to individual signals such as clicks, pulses, airguns, vessel cavitation and engine noise, etc. These values can all be measured in a variety of ways such as peak, peak-to–peak, or RMS and are all dependent on the bandwidth, whether it is single, narrow, or broadband, particularly if values are being compared across studies.

Acoustic signals are often measured impulsively, which, depending on the method of measurement and angle, can produce significant differences (40dB for sperm whales (Madsen et al., 2002b)). Peak-to-peak is often used by the industry to report the calculated source level of their equipment. Root mean square is often used by biologists when they discuss hearing sensitivities, call intensity, or thresholds for hearing shifts. This complicates matters because these numbers are not directly comparable and don't provide the same information for comparisons. Gales et al. (2003) explain this confusion nicely: "the literature on this is confusing…different authors use different units, different measurement types, not stated units or not stated units or measurement types correctly or completely or not comparably with others." This type of inconsistency will be an issue for any manager trying to research effects and present a cohesive plan to address the issue.

A major point of contention between scientists and people in industry is determining how loud is too loud? Human introduction of sound to the oceans (e.g. shipping, drilling, and seismic exploration) could have large impacts on the ocean environment. It is imperative to know how much anthropogenic noise introduction exceeds that with which marine animals can contend. It is especially difficult to try to accurately describe the perception of loudness of a passing vessel or a sonar ping for a marine mammal, for example, particularly since different marine mammals use different methods for signal detection. Even with the ability of conversion from water sound levels to air sound levels, comparison of these levels are still only relative to human perception and cognition. These levels have absolutely no bearing on the perception of the marine animal being exposed to that level of sound. Because sound is measured logarithmically with decibels, an increase (in air or water) of 3dB is a doubling of the power; an increase of 6dB is a doubling of the intensity; and an increase of 10dB is perceived as doubling the volume. It is not what humans perceive as a significant change in sound intensity that is relevant. What is relevant is to understand how much additional noise is introduced through human activity and how that additional noise is affecting the marine environment. Whether this pertains to sperm whales is based on how they use sound in their environment.

Sperm Whale Sound Production and Communication

In 1957, Worthington and Schevill published the first study of sperm whale vocalizations recorded through a hydrophone. They reported that sperm whales make clicks. These clicks are sharp, broadband, impulsive sounds ranging from 400Hz to 25kHz with a central frequency of 15kHz. These clicks can be very powerful with source levels up to 223dB re 1µpa @1m (Møhl et al., 2000) and are, arguably, highly directional (Møhl et al., 2000; Thode et al., 2002). Source levels of sperm whale clicks vary based on the type of click. Usual clicks range from 220-236 dB and can decrease by as much as 40dB between on and off axis detections (Møhl et al., 2000; Madsen et al., 2002b).

Communication

Sperm whales use a variety of patterns for their clicks. Two major functions are communication and echolocation. A breakdown of these click patterns can be found in Table 1. The most common type of clicks is the "usual" type of clicks which is defined as a long train of equally spaced clicks. These usual clicks are thought to be a type of basic ranging sonar or echolocation by some (Backus and Schevill, 1966; Norris and Harvey, 1972; Goold and Jones, 1995; Møhl et al., 2000; Jaquet et al., 2001; Madsen et al., 2002b) and a type of long range communication by others (Watkins, 1980).

A second type of click pattern is called a "creak" or "buzz." These patterns have considerably shorter intervals between clicks and the clicks themselves may be of shorter duration. Sperm whales are thought to use a combination of usual clicks and creaks during foraging dives. These clicks are punctuated by periods of silence during the dive as well. Usual clicks are possibly for searching, long range, for potential prey items. Creaks are used in the final stages of homing and capture. Determining the rate of success is not possible based just on acoustics; however, estimations of foraging attempts are possible (Gordon, 1987, Jaquet et al., 2001; Thode et al., 2002). Creaks can also provide information about the prey capture process. Based on the assumption that inter click interval accounts for the time it takes for the sperm whale to detect the echo of the click, decreasing intervals indicate decreasing distance. There is evidence of this in other odotocetes, but not for sperm whales specifically. However, if the assumption holds true, females generally detect pray within 30m and males between 35 and 40m. (Gordon, 1987; Jaquet et al., 2001).

The third and most variable type of click pattern is the "coda" which is made up of a pattern of clicks grouped together (Watkins and Schevill, 1977). It is thought that sperm whales use codas to communicate socially. Codas can vary by region or clan (group of sperm whales) and are often distinct dialects among groups (Weilgart and Whitehead, 1997; Watkins and Schevill, 1977; Whitehead and Weilgart, 1991; Rendell and Whitehead, 2001; Rendell and Whitehead, 2003). At the surface, sperm whales make codas, “coda- creaks,” rapid clicks, and “chirrups” associated with social activities and mating (Weilgart, 1990; Gordon, 1987).

A final click type identified by Gordon (1987) is a slow click called a “clang.” The clang is a slow, loud, resounding click repeated at 5-8 second intervals. These are distinguishable from regular clicks by their lower frequency distribution and low directionality which may be what allows them to be heard at distances of 20km (Barlow and Taylor, 1998). It is believed that males are the major producer of the slow click, and on the breeding grounds they may comprise up to 74% of the clicks made by males (Whitehead, 1993). It is possible that these clicks have to do with the mating system for either attracting females or repelling males (or both) and possibly acting as an “honest indicator” for male size and fitness as a mate (Cranford, 1999). Goold (1999) suggests that these may be used as long range echo sounders for large objects like other whales, ships, or the bottom. There is still much speculation in this area.

Table 1: Source level values for different types of sperm whale clicks (Madsen et al., 2002a).

Table 1 Estimated source parameters of various male sperm whale click types recorded off northern Norway (*CF* centroid frequency, *BW* −10 dB bandwidth)

Click type	ASL (dB//1 μPa rms)	ASL (energy dB//μPa²s)	Directionality	CF (kHz)	BW (kHz)	Duration τ (μs)
Usual click (*N*[a]=20)	220–236[b]	191–198[b]	High[b]	15	15	120[c]
Creak click (*N*=5)	179–205	145–161	High	15	13	100
Slow click (*N*=6)	175–190	156–166	Low	3	4	500–10,000

[a] Number of sequences that allowed for source parameter estimation

[b] Data from Møhl et al. (2002)

[c] Duration of the p1 pulse

Sound Production

Toothed whales, such as sperm whales, produce a range of clicks, whistles, and other tonal sound. In dolphins, these sounds are produced in the nasal complex (Amundin and Anderson, 1983; Ridgeway and Carter, 1988; Cranford, 2000). A similar function of the large nasal complex in sperm whales has been proposed. In 1957, Worthington and Schevill published the first record of sperm whales producing clicks. Later, in 1966, a more in depth investigation showed that these clicks were broad band and multi-pulsed, ranging in frequency from 0.2-32kHz. It was suggested at that time that clicks might be used for echolocation and possibly as individual identifiers (Backus and Schevill, 1966).

The spermaceti organ is found within the sperm whale head which can comprise up to 40% of the entire length of the whale. It is surrounded by a thick wall of muscle and filled with a semi-liquid, waxy oil. The muscle/tendon layer covers the entire dorso-lateral part of the spermaceti organ and inserts into the connective tissue around and in front of the monkey lips, also referred to as the phonic lips, *museau de singe* (Madsen et al., 2002a). The purpose of the spermaceti has been debated; however, in 1972, Norris and Harvey proposed its crucial role as an acoustic resonance chamber involved in the production and projection of sperm whale clicks. Figure (5) below is a diagram showing the anatomy of a sperm whale head where Mo shows the position of the monkey lips and So represents the spermaceti.

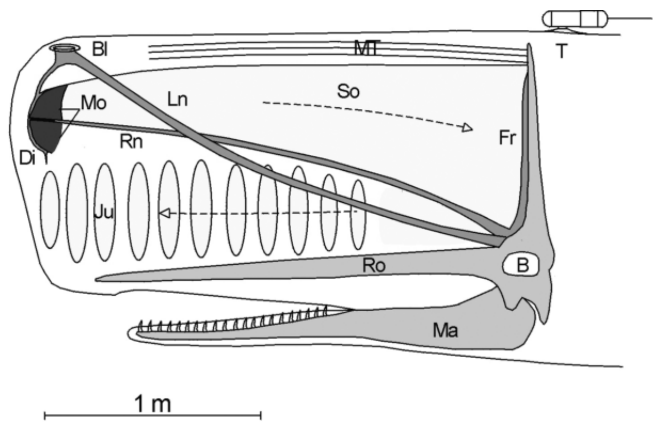


Figure 5: Diagram and explanation of sound production in a sperm whale: Schematic view of the head of a 10 m long sperm whale (Physeter macrocephalus) showing placement of the tag. B, brain; Bl, blow hole; Di, distal air sac; Fr, frontal air sac; Ju, junk; L, left naris; Ma, mandible; Mo, monkey lips/museau de singe; MT, muscle/tendon layer; Ro, rostrum; Rn, right naris; So, spermaceti organ; T, tag. (Madsen et al 2002b).

Norris and Harvey proposed that sperm whale clicks are produced at the phonic lips (*museau de singe* or monkey lips). The phonic lips are a valvular structure located at the front of the head beneath the blowhole. It is proposed that the initial pulse is produced by forced air from the right naris through the monkey lips. The dominant first pulse is then projected into the water while remaining pulses are actually reflections of the first pulse as it is reflected between two air sacs on either end of the spermaceti. Mohl, in 2001, modified this theory, presenting a ‘bent horn’ theory whereby only a small portion of the initial click is released into the water creating a low intensity omni-directional click (P0 Pulse). The majority of the energy is propagated back through the spermaceti organ to the frontal air sac at the front of the skull before being reflected downward and forward into the junk, which acts as a focusing lens, and at which point it propagates forward into the sea water in front of the whale (P1 Pulse). The multi-pulse structure is generated by the interception of a portion of the energy by the distal air sac which is reflected through the spermaceti to the frontal sac which then follows the original path and is emitted as the P2 and P3 etc. pulse (Cranford, 1999; Møhl, 2001; Zimmer et al., 2005). The origin of the click at the phonic lips was verified by Madsen et al. (2003) through studies of a sperm whale neonate in rehabilitation (Møhl et al., 2003). Although the P0 pulse is considered lower energy, it is still detectable over long distances and strong enough to produce echoes from the sea floor and surface. It is generally associated with a lower frequency energy bands.

There is much discussion over the energy distribution in sperm whale clicks. Lopatka et al. (2006) state the range from below 100Hz to above 20kHz with major energy emphasis between 2-8 kHz and 15 kHz (Goold and Jones, 1995; Zimmer et al., 2005). The individual frequencies range from 400 Hz and 2 kHz for males and 1.2 kHz and 3 kHz for females (Goold and Jones, 1995), as well as 1.8 kHz and 2.8 kHz as identified for slow click energy concentrations by Weilgart and Whitehead (1988).

The central frequency for usual clicks varies from 2 kHz (Goold and Jones, 1995) to 5-7kHz (Levenson, 1974; Mohl and Amundin, 1991) and 2-32kHz (Backus and Schevill, 1966; Watkins, 1980). The variation could be due to difference in recording equipment and sensitivity as well as the ability of sperm whales to vary their energy and frequency range (Madsen et al., 2002b). These ranges are also in agreement with audiograms from neonate sperm whales which measured the optimal hearing range from 5-20 kHz (Ridgeway and Carter, 2001). Interestingly, these same neonates exhibited a much lower frequency range for click production. Central frequencies were measured between 300Hz -1.7kHz (Madsen et al., 2003) and 500Hz - 3kHz (Ridgeway and Carder 2001) with both reporting the clicks at a low frequency and low directionality with source levels between 140-162 dB re 1 μPa-m. These clicks are likely unsuited for echolocation; however, they may provide a homing signal for diving conspecifics up to 2km away (Madsen et al., 2003).

As discussed above, while most clicks and click patterns are involved in daily activity, the “clang” as identified by Gordon (1987) may serve a different purpose. To review: the clang is a slow, loud, resounding click repeated at 5-8 second intervals which are distinguishable from regular clicks by their lower frequency distribution and low directionality (Weilgart and Whitehead, 1988). Cranford (1999) suggested that the size of the sperm whale head could only be linked with combined selective pressures for resource acquisition and sexual selection. These loud, low frequency signals with reverberant characteristics are associated with the dimensions of the spermaceti which demonstrate potential heritable characteristics. That is to say, these signals can indicate the size of a whale. Larger size would suggest a more fit individual, better able to survive; and because these signals are size dependent, it is not a characteristic that can be misrepresented. The question then becomes: is sound production an indication of sexual fitness, an ‘honest indicator,’ for female sperm whales to judge their potential mates?

The size of a whale can be determined by its click parameters and that inter-click-interval has a direct relation to size (Gordon, 1991; Rhinelander and Daweson, 2004; Jaquet, 2006; Mathais et al., 2009). While these studies all admit to error and difficulty with calculation, presumably, if mathematical relationships between inter-click-intervals can be derived, it is not unreasonable that individual whales can use the difference in arrival times of conspecific’s clicks to gauge the size of the competition. Estimates of the range of audibility for a clang are 20-60km which assumes a fairly quiet ocean (Barlow and Taylor, 1998; Madsen et al., 2002a). If the sound generation potential increases as the size of the animal increases, the advertisement potential for a large male also increases. Because slow clicks, or clangs, are very low frequency, 1.8-2.8kHz (when compared with regular clicks), their potential range also increases since low frequencies travel further (Weilgart and Whitehead, 1988). These may serve as an early announcement to an area and also as a warning to others that they are about to have company. On a smaller scale, while these clangs can be heard from very far away, it may be that the intensity of the clicks at closer range would serve as the indicator since the female would have more than one male to compare (although this may not matter if there is some innate characteristic in the click she is tuned towards which could be determined over greater distances).

All of that aside, the potential for social-sexual signaling on low frequency communication calls means that sperm whales, like many other whales, are susceptible to the loss of communication from low frequency masking. In a “quiet ocean,” Madsen et al. (2002a) suggest that sperm whales may be able to hear regular clicks to a distance of 16km, creaks to 6km, and clangs out to as much as 60km. These calculations are based on published levels from Urick (1983), with a sea state of 1. Take for example, the slow click: while range cannot be recalculated here, the noise level used is of 43dB re 1 μpa^2/Hz; however, those are ideal conditions which assume no input from shipping either long distance or near field (very close by). The assumption is that the receiver is also experiencing those same conditions, which is not necessarily true if the distance is estimated in 10s of km. It is more plausible that signals in the 2kHz range will have heavy competition from near field weather and, more importantly, anthropogenic inputs such as shipping. Depending on the actual range, signals from these slow clicks may become distorted or lost.

Distant signals are not the only likely obscured signal due to human induced noise. Sperm whales use sound to forage as well. As mentioned, the homing range for a creak for females is generally within 30m and males between 35 and 40m. (Gordon,1987; Jaquet et al., 2001). These calculations all assume a “quiet” ocean. The issue on a small scale may not be whether sperm whales can hear other sperm whales, but whether they can hear themselves. André (2009) found that the detection range for a modeled squid 25cm long, in a seas state of 1 (“quiet” seas), is 1.7 km. Changing natural environmental conditions such as wind or waves would increase the sea state and, as a result, decrease the detection range. Noise from passing ships potentially surpasses noise levels from natural environmental factors and may eliminate detection probability altogether, impacting an individual's ability to hear its own signals, which may negate its ability to successfully locate and capture prey.

It is not only individuals who would be negatively affected by loss of communication space. Small scale cohesion of family groups where young calves are left at the surface for short periods of time require constant contact so that mothers can find their young (Whitehead, 1996). Ridgeway and Carder (2001) and Madsen et al. (2003) both identified neonates with limited frequency range clicks and amplitudes indicating that, at the most, these young whales can communicate at low frequencies over distances of 2km under ideal conditions. Once again, this becomes a case of near field obstruction of intimate contact between family members. A diving sperm whale may be 1km below the surface. A passing ship may be within a hundred meters of a calf at the surface. That ensonified area has the potential to obscure communication among family members, which breaks down cohesion and communication over time.

CHAPTER III

COMPARISON OF SHIP NOISE AND AMBIENT NOISE

The GoM is a busy place: It is home to two of the world's ten busiest ports by cargo volume, the Port of New Orleans and the Port of Houston; and in 2008, these ports hosted a combined 14,000 ships, a number which is likely only to have increased in the past 3 years.

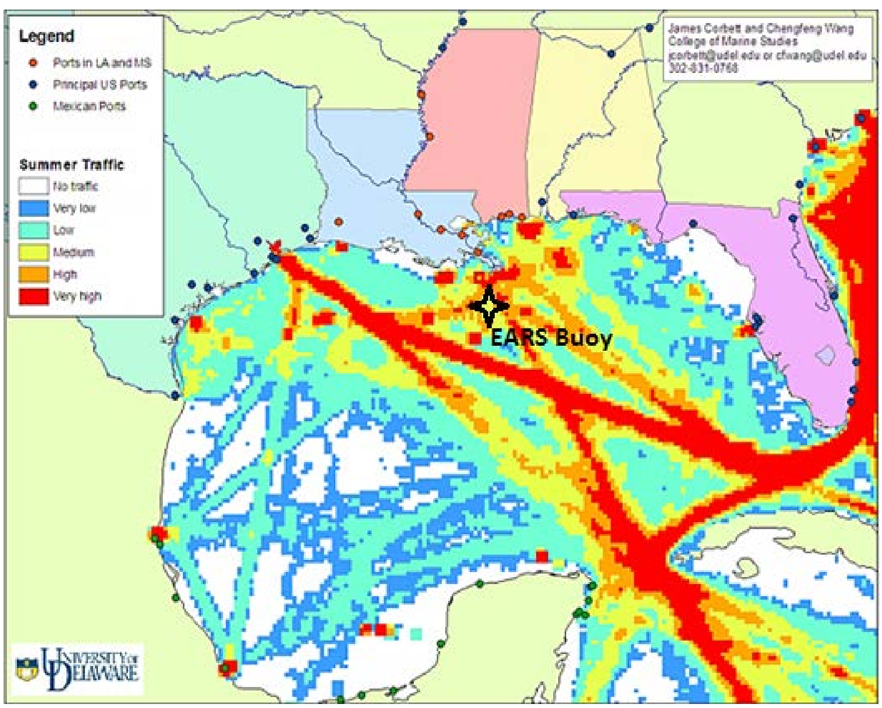


Figure 6: Location of EARS buoy relative to shipping lanes in the GoM.

Figure 6) shows the locations of major shipping lanes in the GoM. The areas in red show areas of highest ship traffic density. These lanes in red clearly connect the Florida Straits with the Port of Houston and Port of New Orleans. Other smaller coastal shipping routes are also apparent in yellow particularly along the Louisiana – Mississippi Shelf. The location of the Navy environmental acoustic recording system (EARS) buoy used to collect the data for this analysis is marked on the figure. Its location is important because it falls within the convergence of multiple shipping lanes which may impact the number and frequency of vessels recorded in the area.

One of the first questions addressed by the data analysis was whether ships could even be detected on recordings from 1000m depth. In order to test whether they were detectible, each hour of data from 2001 was processed using MATLAB to create a frequency-intensity profile and a color plot showing the change of intensity with frequency over time for 3600 seconds (60 minutes). Plots with potential detectible ships were noted and times when ships were thought to be present were verified aurally through listening to the sound files associated with each of the time periods. A separate database was kept noting the hour, presence or absence of ships, the number of ships, and the sound file in which the ship was first aurally detectable. An initial pilot study was completed for the first two days of acoustic data to test whether an hour sample size was sufficient to resolved differences in ship presence and absence through analysis of average noise levels per hour in dB.

Part I: Pilot Acoustic Analysis

Introduction

The data for 2001 season consist of 36 days of continuous acoustic recordings beginning on July 17th. The acoustic package recorded at 11.725 kHz and produced reliable recordings up to 5 kHz. In order to analyze daily fluctuations in ambient noise, the average sound level of the first ten minutes of each hour was calculated for each hour during the 36 day sample period.

The assumption of random sampling was made based on “blind” sampling of the first ten minutes. The data were used regardless of presence or absence of a vessel. Because ten minutes may not be representative of the activity that occurs during the full hour, each hour was also averaged and compared with the ten-minute sample. Historical weather data were used to determine when tropical storms or hurricanes passed through the area. According to NOAA records of hurricanes for the summer of 2001, there were no anomalous events during the two days analyzed for this pilot study. Because noise level varied by frequency, standard 1/3 octave central frequencies were chosen to represent frequency bands within the useable range. Central bands concurrent with known sperm whale frequency peaks were specifically chosen to represent changes that might have an effect on the population. These frequencies, as identified by the literature, are 400 Hz and 2 kHz for males and 1.2 kHz and 3 kHz for females (Goold and Jones, 1995), as well as 1.8 kHz and 2.8 kHz as identified for slow click energy concentrations by Weilgart and Whitehead (1988).

The goal of this pilot analysis is to determine if samples with ships are significantly louder than times without ships. To do this, three hypotheses were tested:

1. There will be no significant difference in loudness between the ten minute sample and the hour sample for times when there is a ship in the first 10 minutes, but not in the remainder of the hour.

2. There will be no significant difference in loudness between the ten minute sample and the hour sample for times when there was no ship present in either the 10 minute or hour file.

3. There is no significant difference in loudness between ten minute samples without ships that are part of hour samples with ships.

Methodology

Samples are from day 199 and 200. Not knowing what would be detectible in the files, the analysis was started from the beginning of the useable data. For each hour, two samples were taken. The first is an average of the first ten minutes of each hour. The second is an average over the entire hour. This was performed in part to test sampling methodology but also to test the question of whether a ten minute sample could be considered representative of the average noise over the entire hour.

The hydrophones on the buoys recorded continuously for 36 days at a sampling rate of 11.725 kHz. Based on the theory of the Nyquist frequency, the data should be usable up to approximately 5 kHz. In light of this, several specific frequencies were sampled to demonstrate the change in sound level with increase in frequency. Frequencies were chosen based on the published central frequencies of recognized 1/3 Octave bands (Pierce, 1983). That these same frequencies will be used throughout the analysis is particularly important if sound exposure levels over a frequency range are to be calculated. Using recognized frequencies allows the results to be compared with similar analysis conducted in other locations. In addition, frequencies closest to those used by sperm whales were selected. Sperm whale clicks contain concentrations of energy at certain frequencies. Some of these frequencies include: 400Hz, 1.2 kHz, 1.8 kHz, 2 kHz, and 3 kHz. The frequencies used in this analysis are: 25Hz, 50Hz, 125Hz, 160Hz, 250Hz, 315Hz, 400Hz, 800Hz, 1250Hz, 1600Hz, 2000Hz, 3000Hz and 4000Hz.

Data analysis began on day 199 at 02:00. For each hour, a ten minute and an hour average were calculated. In addition, a spectrogram was created for visual detection of potential ships, air guns, and sperm whales. For each hour, data were visually and aurally verified for the presence of ships. For each hour, it was noted whether there was a ship in the first ten minutes and whether a ship was detected for the rest of the hour excluding the first ten minutes. In addition, notes were made regarding presence/absence of sperm whales (indicated by their clicks) and air guns. Details regarding the size of the sperm whale group and potential range, close or far, were estimated as well as possible group size, single (for single animal), few (2-3 distinct animals), medium (estimated 4-6) or large (too many to count). Airguns were described as being distant, as sounding like rolling thunder, as close shots, and whether there was an echo. These data were used in later analysis for selecting time periods appropriate for the analysis.

Several statistical tests were performed to compare different groups of data within the sample. The first test was for normality to establish whether groups of data are normally distributed. Then, data from the ten minute sample were compared to the hour sample for each frequency to determine whether there was a difference between the averages of the two sampling methods. Because the data could be broken into three separate groups depending on whether ships were present and when, three additional comparisons were performed. The three groups were defined as: 1) those where ships were present in the ten minute file and by extension present in the hour file; 2) those where no ship was present in the ten minute file but were present in the remainder of the hour; and 3) and those where no ship was present in either the ten minute file or the rest of the hour (Table 2). Lastly, the data were broken into groups defined by the sample period, either ten minutes or hour. Then, files with ships were compared to files without to see if there was a difference in sounds intensity.

Table 2: Comparison of presence/absence of ships by ten minute and hour files.

Comparisons	10 Minute File	Hour File
1st comparison: Ships Present	Yes	yes
2nd Comparison: Ship Present	No	Yes
3rd Comparison: Ships Present	No	No

Results

While data were continuous and randomly sampled, of the thirteen frequencies sampled, most were normally distributed; independent-sample T-tests were performed to test for significant difference among groups. For the comparison of all ten minute files with all hour files, there was no significant difference in sound intensity. Likewise, comparisons of ten minute files and hour files that both contained ships or that both did not contain ships in either were also not significantly different across all frequencies. The comparisons between ten minute files without ships and hour files with ships were significantly different depending on the frequency tested. For the frequencies 25Hz, 50Hz, 125Hz and 160: there was no significant difference ($P>.05$). For the frequencies

250Hz and 315 Hz: the difference is significant at the 90% confidence ($P<0.1$). Lastly, for 400Hz and above: the difference is significant at the 95% confidence level ($P<.05$). This is interesting because male sperm whales use 400Hz and above for their low frequency regular clicks meaning that ships create a significantly louder environment at the same bandwidth in which sperm whales communicate.

Further analyses were completed comparing times with ships to times without ships based on the time period. The sample was broken into groups with and without ships in the files. Thus, ten minute files with ships were compared with ten minute files without ships and the same for the hour long files (Table 3). In both cases, there were significant differences at the 95% confidence interval indicating that times when ships pass are significantly louder than times without ships.

Table 3: Explanation of secondary comparison of files with and without ships based on time period.

Comparisons	**Files with Ships**	**Files without Ships**
1^{st} Comparison	10 minute file	10 minute file
2^{nd} Comparison	hour file	hour File

Discussion

In light of the significant differences between ten minute files and hour files, the remainder of the analysis will be performed on hour long files. No sub-sampling will be done unless it is specifically to subsample events like ship passages which are discussed later in the chapter.

Part II: Full Acoustic Analysis

Based on the pilot analysis of days 199 and 200, the remaining 34 days were analyzed hour by hour for presence or absence of ships. Once each hour had been characterized, statistical tests were run to determine whether, over the 36 days of data, including the days already analyzed, the statistical differences found in the pilot study could be verified. To do this, the data were broken into three, 10-day sections so that results could be verified through duplication. Because the first and last days of data collection were incomplete, they were not included in the analysis, thus a total of 30 days of data were analyzed. Breaking the days from 200 to 230 into 10 day sections was the simplest way to divide the data into even groups for analysis. As seen in the pilot study, the assumptions for equal variance and normal distribution were not always met. Thus, non-parametric comparison of means was performed to compare the data sets. The data were broken down as follows (Table 4):

Table 4: Breakdown of 10-day analysis sections by presence absence of ships per hour per section.

Days Analyzed	**Total Hours**	**Presence/Absence**	**Hours**	**Percent**
199-200	285	No	125	44%
		Yes	160	56%
211-220	239	No	134	56%
		Yes	105	44%
221-230	240	No	135	56%
		Yes	105	44%
Combined days	764	No	394	**52%**
		Yes	370	**48%**

Based on the breakdown between days (Table 4), there is some variability in ship passages; however, overall for the time period, there are roughly the same number of hours with ship passages as without.

As discussed in the pilot analysis, a 1-sample Kolmogorov-Smirnov test for normality was performed for each of the 10 day subsets (Table 5).

Table 5: Complete statistical analysis results for the comparison by 10-day section across all 13 frequencies.

Day 199-210 Test Statistics[a]

	Hz25	Hz50	Hz125	Hz160	Hz250	Hz315	Hz400	Hz800	Hz1250	Hz1600	Hz2000	Hz3000	Hz4000
Mann-Whitney U	6283.500	4476.500	3810.500	5956.500	4017.500	3142.500	3433.500	3980.500	5373.500	5873.500	6040.500	6907.500	6173.500
Wilcoxon W	14158.500	12351.500	11685.500	13831.500	11892.500	11017.500	11308.500	11855.500	13248.500	13748.500	13915.500	14782.500	14048.500
Z	-5.383	-8.000	-8.965	-5.857	-8.665	-9.932	-9.511	-8.719	-6.701	-5.977	-5.735	-4.479	-5.542
Asymp. Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000

Days 211-220 Test Statistics[a]

	Hz25	Hz50	Hz125	Hz160	Hz250	Hz315	Hz400	Hz800	Hz1250	Hz1600	Hz2000	Hz3000	Hz4000
Mann-Whitney U	3885.000	2756.000	2334.000	5142.000	3507.000	2419.000	2750.000	4301.000	5495.000	5711.000	5776.000	6329.000	5770.000
Wilcoxon W	12930.000	11801.000	11379.000	14187.000	12552.000	11464.000	11795.000	13346.000	14540.000	14756.000	14821.000	15374.000	14815.000
Z	-5.938	-8.066	-8.862	-3.569	-6.651	-8.702	-8.078	-5.154	-2.903	-2.496	-2.373	-1.331	-2.385
Asymp. Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000	.004	.013	.018	.183	.017

Days 221-330 Test Statistics[a]

	Hz25	Hz50	Hz125	Hz160	Hz250	Hz315	Hz400	Hz800	Hz1250	Hz1600	Hz2000	Hz3000	Hz4000
Mann-Whitney U	4563.000	2745.000	1770.000	4637.000	1481.000	948.000	794.000	1033.000	1796.000	2319.000	2322.000	2639.000	2118.000
Wilcoxon W	13474.000	11656.000	10681.000	13548.000	10392.000	9859.000	9705.000	9944.000	10707.000	11230.000	11233.000	11550.000	11029.000
Z	-4.588	-8.035	-9.884	-4.447	-10.432	-11.442	-11.734	-11.281	-9.834	-8.843	-8.837	-8.236	-9.224
Asymp. Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000

Although the data for some frequencies showed both normal distribution and equality of variance, not all frequencies for all hours, nor the same frequencies across all hours, were consistent in their distributions. Thus, a non-parametric, independent sample, Mann-Whitney U Test was performed to test for significant difference of means between hours with ships and hours without ships.

With the exception of the 3000Hz sample from days 211-220, all other times and frequencies are significantly different between hours with ships and hours without ships at the 95% (P=0.05)confidence level; and all comparisons with the exception of 4 frequencies (1600Hz, 2000Hz, 3000Hz and 4000Hz) on days 211-220 were significantly different at the 99% confidence interval (P= 0.01). To further confirm the results of the pilot test using a parametric Students T-Test, the data were also compared parametrically and the same results of significant difference at the 95% confidence level and 99% confidence level were consistent across the board including the variations for the frequencies and time period discussed above. Based on this analysis, hours with ship passages are statistically significantly louder than hours without ships.

Ambient Noise Variability Analysis

One of the issues when dealing with environmental conditions is to understand the variability inherent in the system. Many sound-scapes for an area are represented as an average over long periods of time such as weeks or months. While this is helpful for understanding long term trends or seasonal changes, it does not help to understand small scale variability that would affect marine animals on a daily or hourly basis. The statistics showed that hourly noise variability based on the presence or absence ships is an actual phenomenon. Therefore, it is important to take a closer look at overall variability within the system to see if shipping could be a major contributor of noise.

The first step was to plot all hours across all 13 frequencies to look for patterns of variation. There are several different noise distribution patterns apparent in Figure 7: Hourly noise variability per hour by frequency. The first is the separation of colors from the top of the graph to the bottom. These show noise intensity by frequency. Lower frequencies are noisier than higher frequencies because the energy in the noise attenuates more slowly at lower frequencies allowing it to be detected at higher intensities further away, such as at the bottom of the ocean. Frequencies above 1000Hz attenuate more quickly through absorption so they do not travel as far and are not as loud farther away from the source. It is also clear that the noise in each frequency band appears to vary together; in other words, when the environment is louder, it is louder in all frequencies at the same time. This is a reliable indicator that the recording equipment and analysis are accurately representative across all frequencies. It is not surprising to see that noise levels vary consistently across all frequencies and is what would be expected when a broad band noise source, like near-field shipping, is introduced. Another obvious characteristic of the plot is that the bell curve increases and decreases in the middle of the plot in the higher frequencies with a concurrent decrease in lower frequencies.

During the 2001 recording period, Tropical Storm Barry passed through the eastern GoM. Tropical storms have sustained winds which propagate from the center of storm outwards. Although Barry did not pass over the buoy location, increase wind and waves likely contributed greatly to the environmental noise conditions in the GoM and are likely the cause of the uniform sustained pattern of increasing and decreasing noise. Likewise, much of the low frequencies noise propagating to depths of 1000m is from vessel traffic passing near the buoy. The safety issue associated with the presence of Barry likely resulted in fewer vessels and may be a contributing factor to the reduction in lower frequency noise during that time.

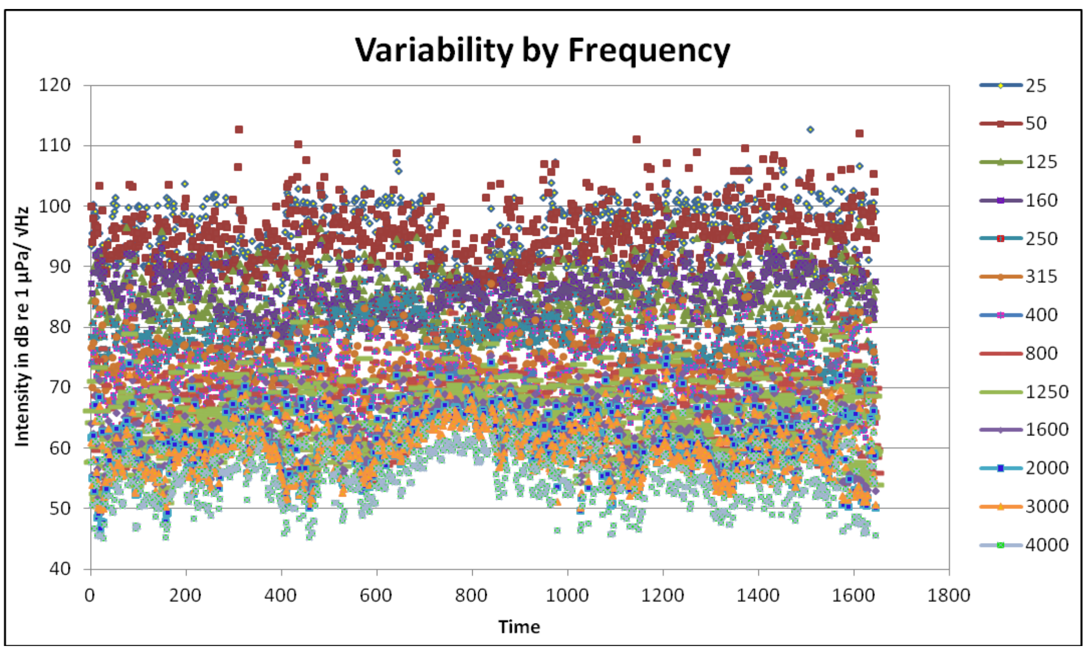


Figure 7: Hourly noise variability per hour by frequency.

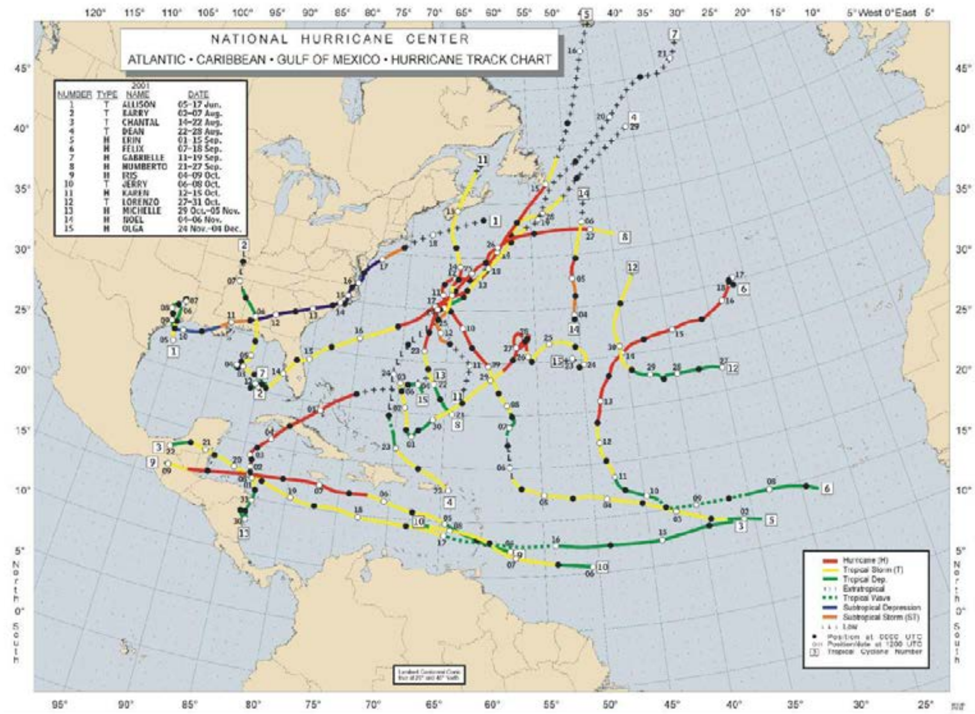


Figure 8: Paths of hurricanes through the Atlantic and Gulf of Mexico in 2001.

Inter-Hour Noise Variability

For the second part of the analysis, the first eleven day period was used to see whether hour to hour environmental (e.g. wind, waves or distant shipping) variability might be an important factor in overall variability. The first eleven days were used because no major storm systems passed through the GoM during that time [Figure 8)]. Based on the graph, there is obvious variability from hour to hour. The range in hourly noise average for the 1250Hz frequencies varies from approximately 50 dB to 81 dB re 1 µpa/ √Hz. As was discussed in previous sections, a decibel (dB) is a logarithmic measurement of intensity or level (of sound in this case). An increase of 10dB is equivalent to a doubling of the perceived volume. Figure 9) shows that throughout the eleven day period, there is a range over which sound volume changes that, at times, is double to three times over the quietest times. This demonstrates a large range of variability in the environment on a small scale.

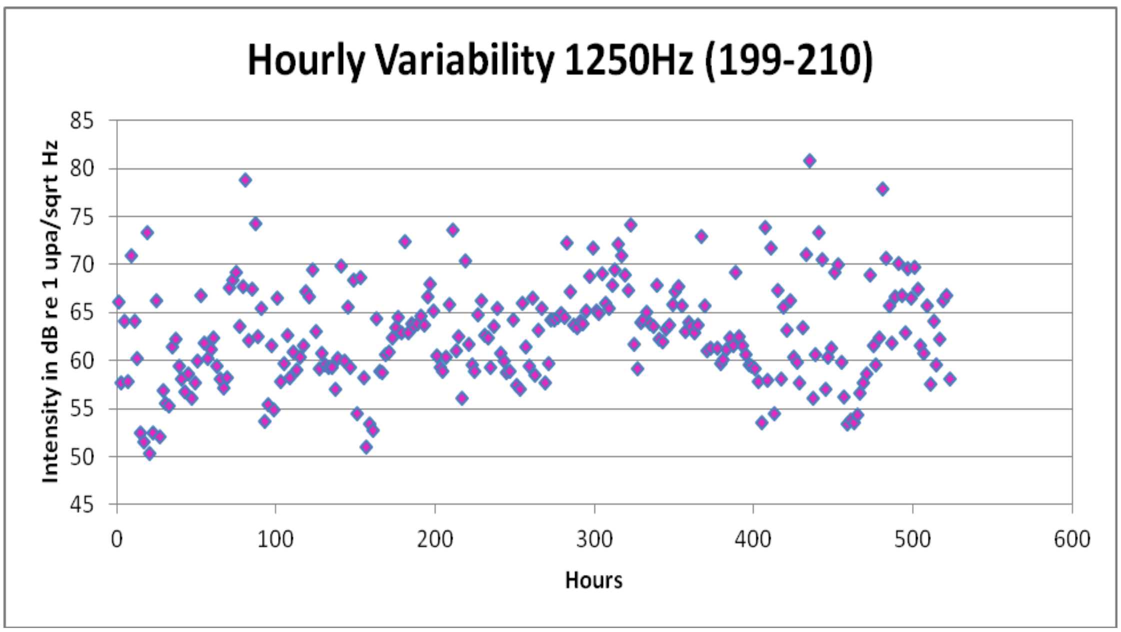


Figure 9: Hourly variability for the 11 day period from day 199-210 at the frequency of 1250Hz. Each pink dot represents the noise level at an individual hour.

The third part of the analysis was whether environmental variability such as noise from changes in wind, waves, or cavitations was responsible for the hourly variations. To do this, anemometer data were taken from a NOAA surface buoy in close proximity to the site of the EARS buoy. By using the daily wind averages for the same time period, and extrapolating noise input from the Wenz scale, a comparison was made between noise from environmental factors and average measured noise from the buoy. Similar analysis was performed previously to determine whether wind effects from hurricanes were measureable from the same buoy. There was a significant increase in noise during hurricanes, validating that these types of measurements are possible from deep moored buoys (Newcomb et al., 2007).

To compare the measured noise with the estimated environmental noise, each subset of data was converted from dB into µPa so that the subtraction of pressure could be executed on a linear scale. The final difference was then converted back into dB and plotted against the average measured noise.

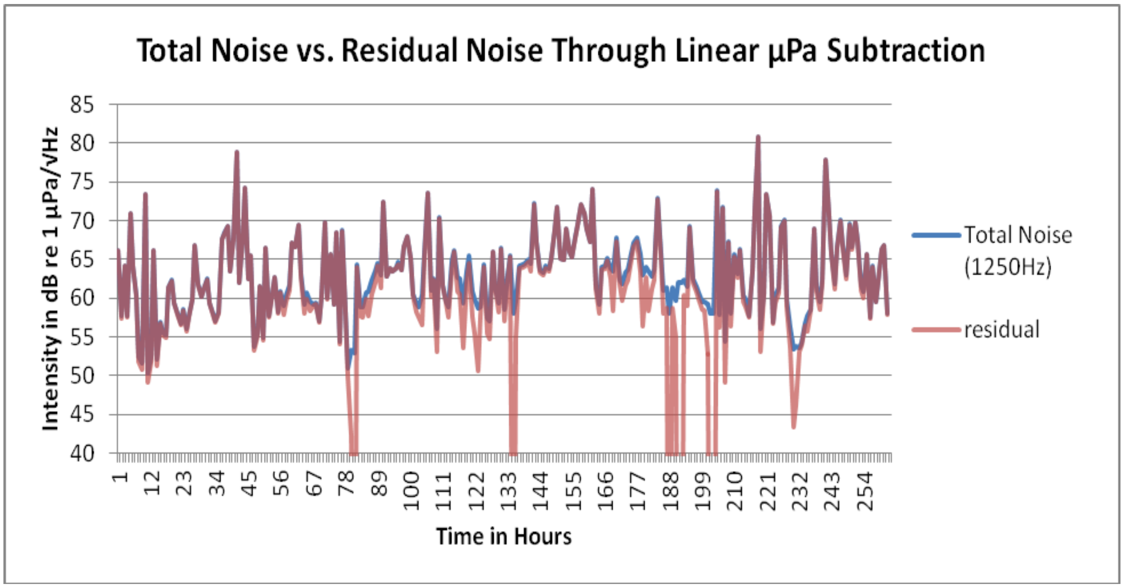


Figure 10: Residual noise after environmental noise input has been accounted for compared with total noise. The areas on the plot where the blue line differs from the red are times when noise levels are accounted for by environmental noise.

The graph above, Figure 10), shows the overlapping lines for the average measured noise and the "left over" noise after the environmental noise measured from the buoys has been subtracted. Where the red line drops away from the blue line are times when changes in environmental conditions explain variations in the noise level. When the red line completely falls off the graph are times when all of the noise in the system is accounted for by environmental input (e.g., wind, waves, or distant shipping). While there are many deviations from the line representing total noise, those times where the lines overlap indicate hours where some other noise source is primarily responsible for the measured noise, and therefore, a major contributor to the variability in the system.

Another way to look at residual noise in the system once environmental noise has been accounted for is a subtraction in dB. While residual intensities in dB are not necessarily representative of the power in the system (because a linear subtraction in dB will not accurately represent the difference); it does offer a helpful visual representation. The graph in Figure 11), below, the closer the blue line is to zero, the greater the amount of noise that can be attributable to environmental factors (e.g., wind, waves, or distant shipping). There are clearly some hours in which environmental factors overwhelm any other anthropogenic or biologic (e.g., sperm whales can be quite loud) input into the system. However, there are also many times when the noise in the system is not explained by changes in environmental conditions. It is possible that such extreme changes may have more to do with the input of anthropogenic noise from passing vessels and that these represent the 48% of the time when statistical differences exist between background noise levels and ship noise (see above: 48% of the files analyzed had ships present).

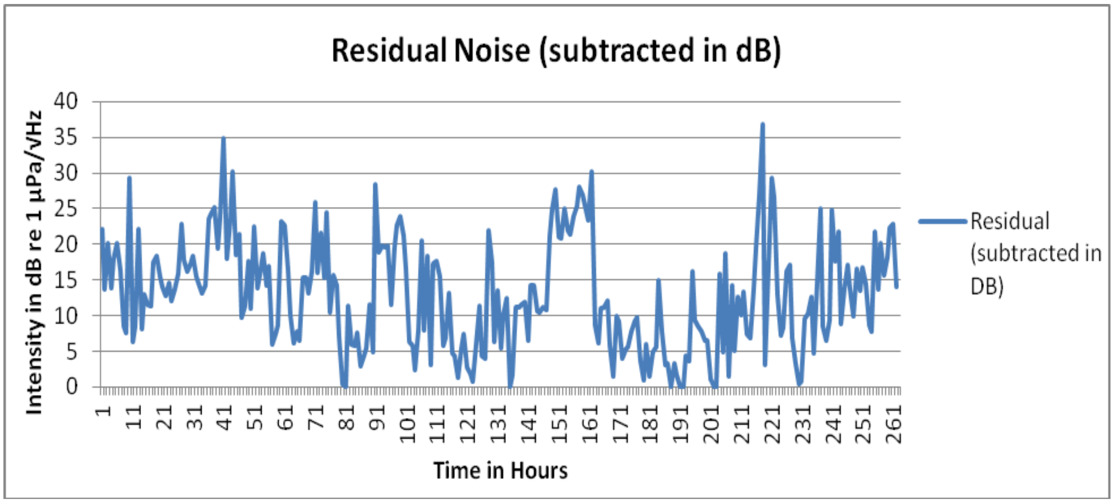


Figure 11: Results when residual noise is subtracted from total noise. Times with near zero noise are times when environmental factors account for the noise recorded by the buoys.

Ship Metrics Analysis

Once the potential for shipping noise to influence noise levels in the marine environment was established, actual ship passages needed to be analyzed. To do this, each hour of each day was processed into a sound file and a color plot. Hours with ships were reviewed aurally and visually for times when ships were visible, audible, and identifiable as a single ship passage. Hours with multiple ships were analyzed, but each ship needed to have individually identifiable peaks. In Figure 12), two ships can be seen during the hour sample. Time is on the vertical axis, in seconds, and frequency is on the horizontal axis. The colors correspond with the amount of noise: warmer colors show time and frequencies with higher noise content; cooler colors show times and frequencies with less noise. The colorbar on the right shows the intensity in dB associated with each color.

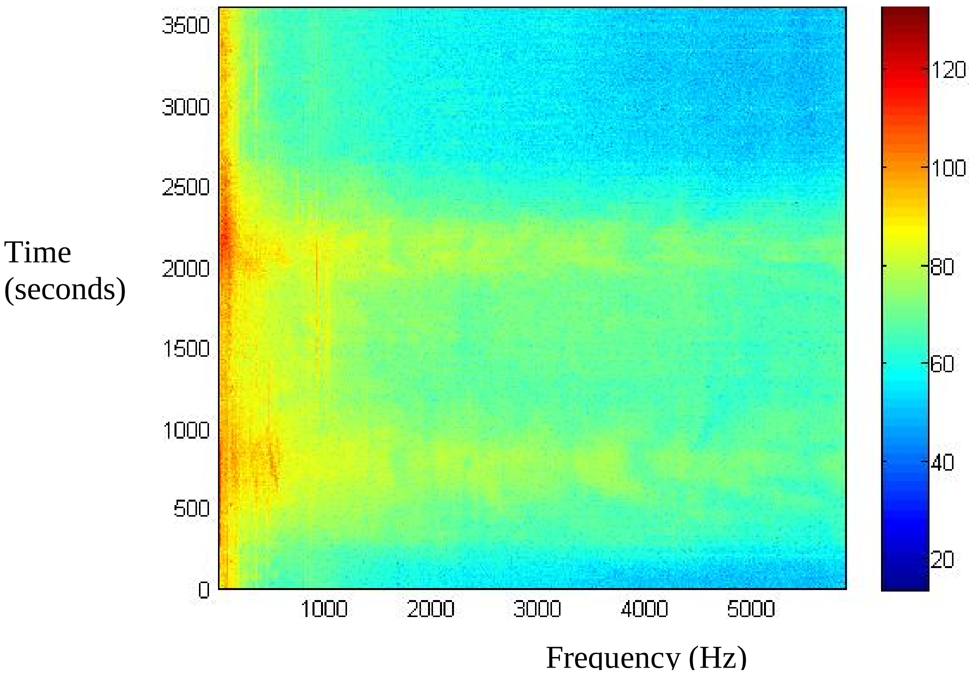


Figure 12: Spectrogram colorplot showing ships passing over buoy.

Once ships were identified, the hour was sub-sampled to isolate just the ship passage and the intensity for three different frequencies. The frequencies were chosen based on those identified by the literature as frequencies with energy peaks. They are 400 Hz, 1250 Hz, and 2000Hz (Goold and Jones, 1995; Weilgart and Whitehead, 1988). These frequencies also overlap with published frequencies for juvenile sperm whale communication (Madsen et al., 2003). For each ship passage, four major parameters were measured [Figure 13)]: 1) Total time for ship passage; 2) Average baseline intensity; 3) Maximum received level intensity; and 4) Duration of maximum received level. These metrics are important for understanding what a whale, or other marine organism experiences when a ship passes through its habitat. Identifying whether ships pass quickly or slowly, whether they can be heard at great distances, and the duration of the passage can explain where animals would be exposed to their maximum source levels. In order to measure these parameters, each ship passage was graphed in excel.

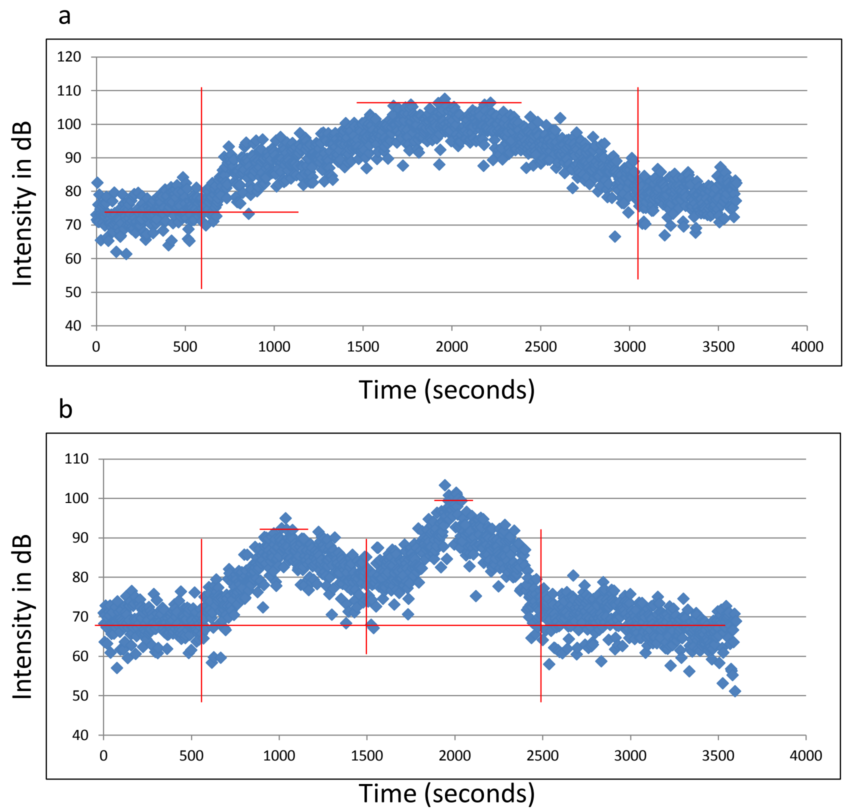


Figure 13: Plots of ship passages where intensity is a function of time as the ship passes over the buoy. The top passage is for a single ship; the bottom passage is for two ships.

The red lines in the figure indicate where measurements were taken. The average baseline was taken at the midpoint of the lowest portion of the graph. This would indicate the average noise level either before or after the ship passed. Often, the levels were not the same, and so the lower of the two averages was used to represent a baseline value. These averages were compared with the averages from the hours without ships used in the statistical analysis [the first part of the full analysis] and were found to be very similar (+/- 3dB). The duration of the ship passage was measured from the first deviation from the baseline with a positive slope (where the entire graph showed an apparent positive shift) to the end of the negative slope (where the graph resumed a continuous horizontal pattern).The maximum received (MRL) was chosen based on the highest intensity level that was repeated throughout the peak, or, the mode of the MRL. The duration of the MRL was calculated from the time when the mode intensity of the MRL began to when the intensity dropped below that level. These measurements were not used for any statistical calculations but instead, were designed to clarify the type of noise level that is created when a vessel passes. This type of information is useful for understanding short term noise variations and their presence relative to short term sperm whale behavior such as diving, feeding, socializing, or resting.

The first verification before moving forward was to plot the baseline intensities against the MRL to see whether there was any significant separation as suggested by the statistics. The three different frequencies (400Hz, 1250Hz, and 2000Hz) were plotted on the same graph. The lower grouping of points on Figure 14) is from the baseline measurements; the upper is from the MRL measurements.

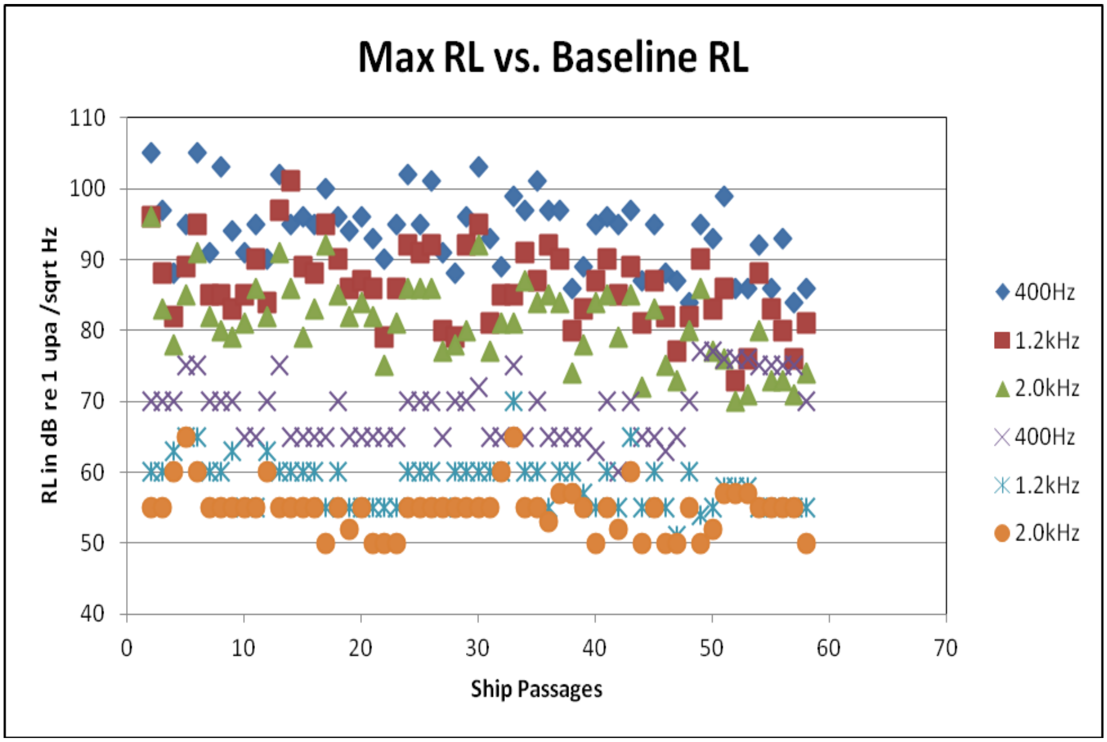


Figure 14: Comparison between MRL and baseline level measurements of noise. Each symbol represents a different frequency and each marker on the chart represents a different ship passage.

From the Figure 14), the separation between baseline and MRL is clear. Although there is some overlap with the 400Hz from the baseline and the 2000Hz from the MRL, these measurements are not directly comparable since they are from different frequencies and the statistical comparisons were between the same frequencies.

The variation in each frequency is explained by each point emanating from a different ship passage. Radiated noise will depend on environmental conditions, source level of the vessel, direction of travel, and distance of the ship from the buoy which will all produce changes in the perceived noise level. In addition, to be representative, a range of ships was chosen for analysis, some with higher MRL than others, which explains the variability in the intensity levels.

Ship Passage and Noise Emissions

The next two analyses were for total ship passage time and for the MRL duration. For the first, 56 ship passages were analyzed across the same three frequencies. Of these, there were 8 time periods where more than one ship passed (either 2 or 3 ships). These combined ship passage times were included in the analysis since there was no break where the intensity level returned to the baseline between/among each ship. Figure 15), below, shows the passage distribution by frequency.

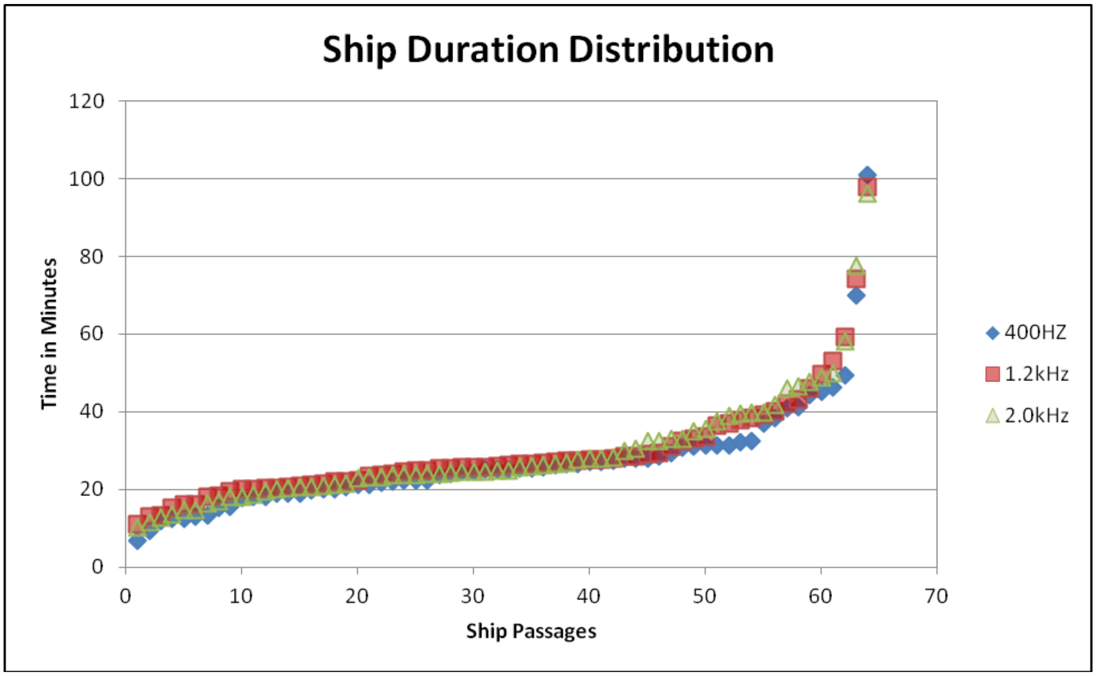


Figure 15: Distribution of ship passage length for each of the ship passage at each of the three frequencies.

From Figure 15), it is clear that most of the ship durations per ship passage overlap despite frequency. The differences are due to variation in sound transmission at different frequencies. Figure (15) shows that there is great variability in the time it takes for a single ship or group of ships to pass by. Only 8 of the passages were from combined ships, and there were individual ship times that were longer than combined times. The majority of the ship times fall between 20 and 50 minutes. A typical sperm whale dive is approximately 45 minutes, with 8-10 minutes spent resting on the surface. The observed range of ship times lasts from half to more than an entire dive cycle. These results suggest that ship passages may have a major effect on sperm whales during their deep foraging dives. This impact depends on several factors including the loudness of the ship during the dive time. If ships take a long time to approach and only a short time to pass directly over, the impact may be minimal because the intensity levels during the passage are low. The following figure, Figure 16), shows the percent of the ship passage during which the MRL was received by the buoy. For this analysis, only the 57 individual ship passages were used.

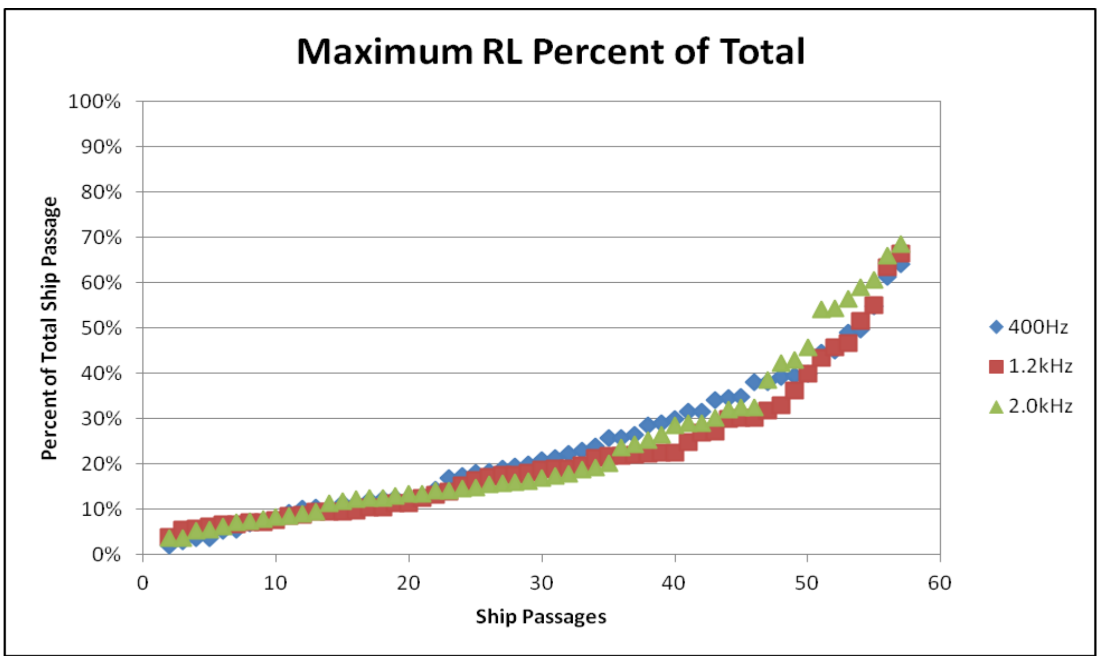


Figure 16: Distribution of the percent of time per ship passage of MRL per frequency.

Once again, the three colored symbols represent the three frequencies analyzed. The distribution of the graph shows that there is a wide range of MRL percentage per ship passage, from below 10% to more than 60%. Depending on the intensity of that MRL, the long duration of high intensity noise input may affect sperm whales during their dives. The second analysis is to determine how much louder those MRL intensities are than the baseline. As in the analysis for environmental noise contributions, it is possible to do a straight linear subtraction of the baseline level from the MRL level to calculate the increase in dB during vessel passages. If the analysis is performed this way, the results for each of the three frequencies are shown in the corresponding figures, Figure 17), Figure 18), and Figure 19).

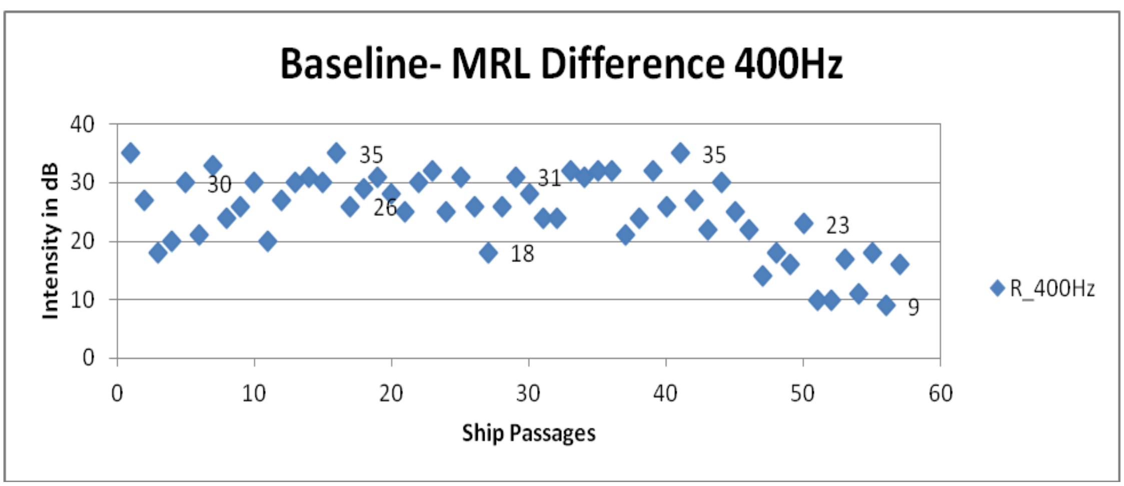


Figure 17: Difference between the MRL and baseline noise levels for each ship passage at 400Hz.

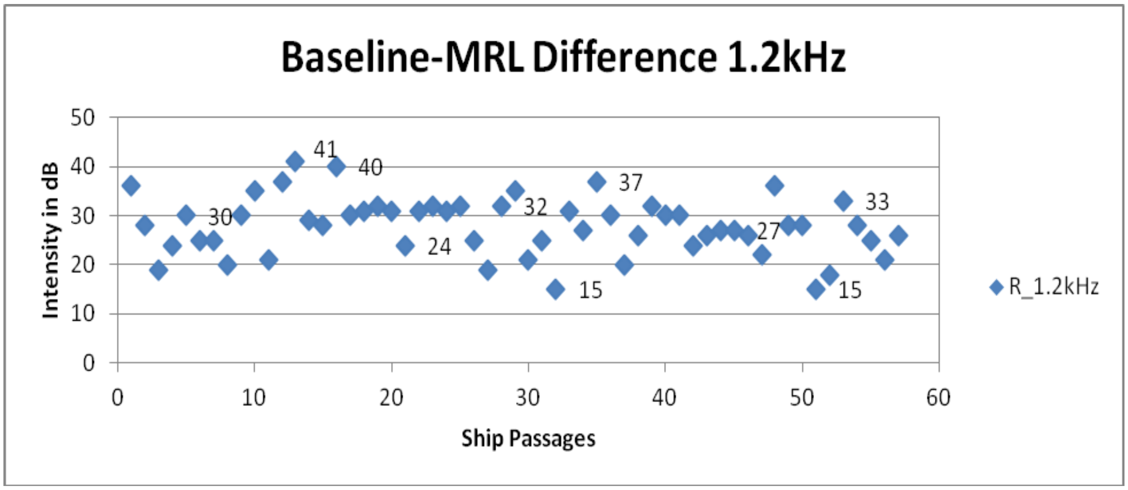


Figure 18: Difference between the MRL and baseline noise levels for each ship passage at 1.2kHz.

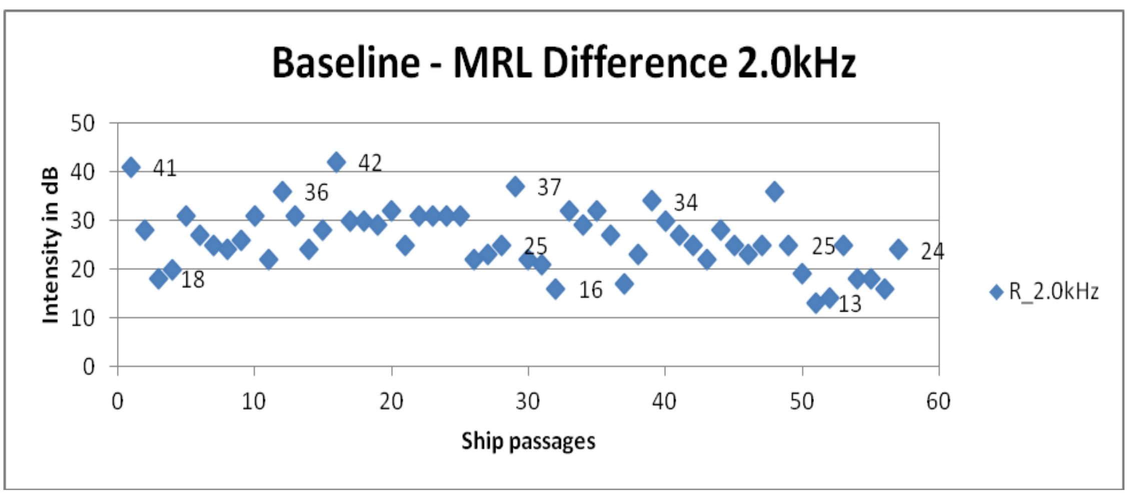


Figure 19: Difference between the MRL and baseline noise levels for each ship passage at 2.0hKz.

As with the shift in average hourly noise, there is variability in the noise intensity from the vessels as well as differences in background, environmental noise which is shown in the wide range of increase in intensity as ships pass over the buoys. While the dB range over which the noise intensity changes is similar among all three frequencies, the higher frequencies show a slightly larger shift which is expected because there is more noise present in the lower frequency bands to begin with (due to distant shipping and seismic activity). While this type of linear comparison is useful for a general understanding of variability, it is not entirely accurate.

In order to understand the magnitude of the increase in noise, a review the mathematical relationship for adding dB is helpful. For example, if the background noise is equal to 20dB and a ship passing over the top is also equal to 20dB, the total noise level, when added together, is 23dB. Thus, an increase of 3dB represents a doubling of the intensity. When two intensity levels are very different from each other, for example 55db and 105 dB, the difference, if the background is subtracted from the noise, the difference is very small because the background becomes insignificant in comparison to the noise. This becomes apparent when the comparison of background and noise levels is performed properly by converting out of dB and into pressure (which is linear), doing the subtraction, and then converting back to dB. The results of this calculation are shown in the following three figures, Figure 20), Figure 21), and Figure 22)

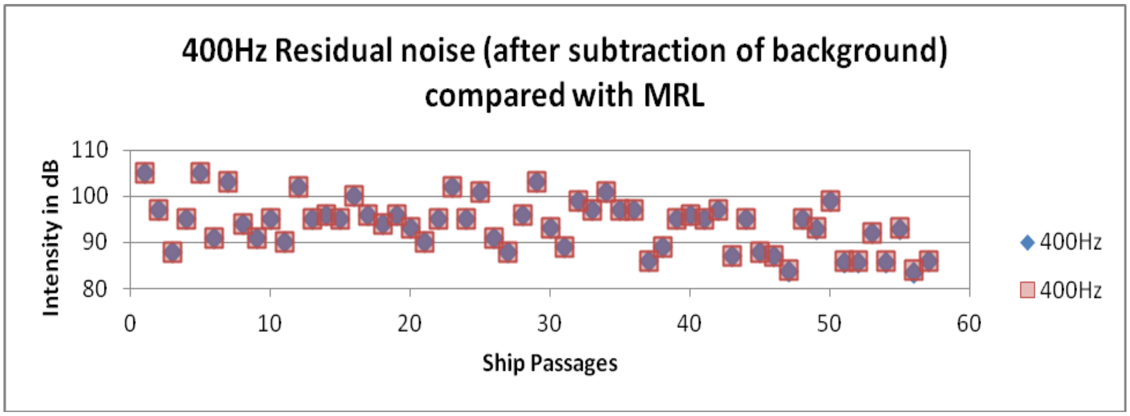


Figure 20: Comparison of background and MRL using appropriate subtraction methods shows complete overlap at 400Hz.

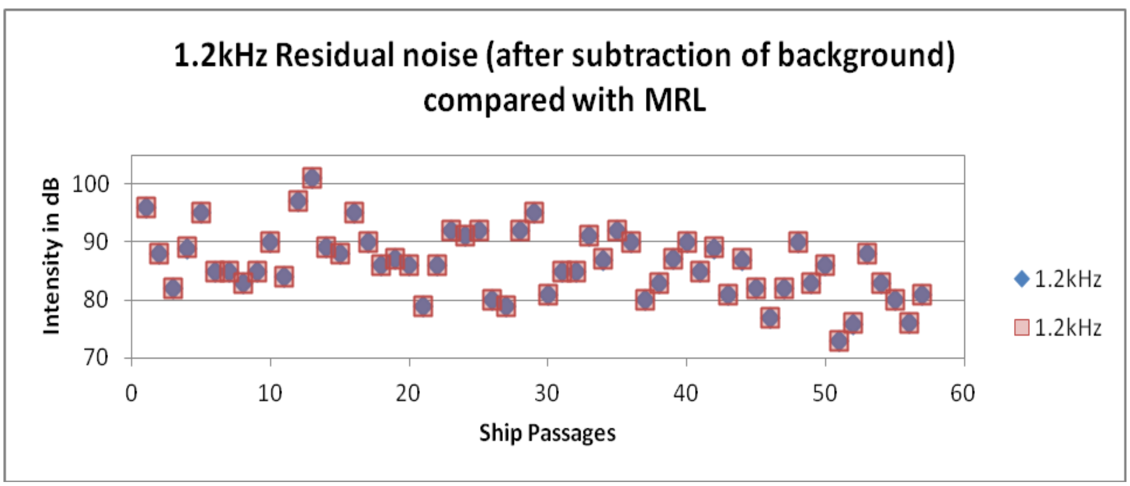


Figure 21: Comparison of background and MRL using appropriate subtraction methods shows complete overlap at 1.2kHz.

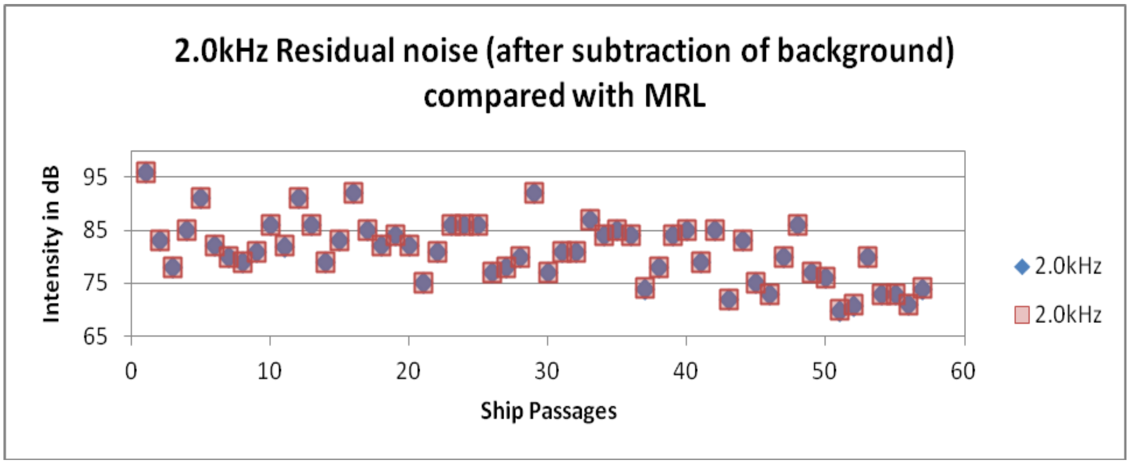


Figure 22: Comparison of background and MRL using appropriate subtraction methods shows complete overlap at 2.0kHz.

The plots show the nearly complete overlap between the measured MRL for each ship passage and the difference between the MRL and baseline when subtracted in pressure and converted back to dB. An overlap like this indicates that the intensity increase during ship passages is so much greater than the background that it becomes essentially insignificant and that the vast majority of noise in the system is due to the passing ships. Comparing the straight dB subtraction and the above plots -- Figure 20), Figure 21), Figure 22), the discrepancy between the results is obvious. The following figures, Figure 23), Figure 24) and Figure 25), plot the two differences against each other. The higher values in blue represent the residual noise when the intensities are converted to pressure and back to dB. The lower values in red show the results of the straight dB subtraction.

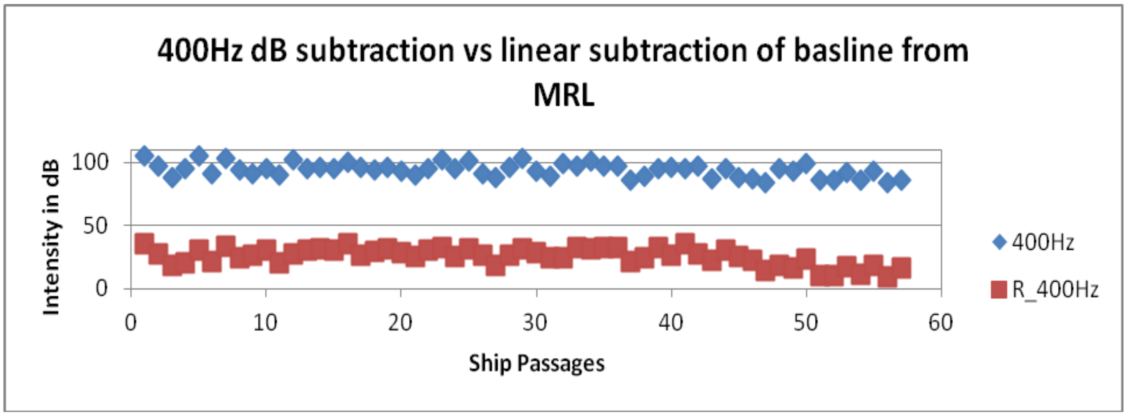


Figure 23: Discrepancy between the two subtraction methods. Red lines are subtraction methods in dB only, blue is with proper conversion. The results show that the correct method for subtraction yields a noise level twice as high as the straight dB subtraction for 400Hz.

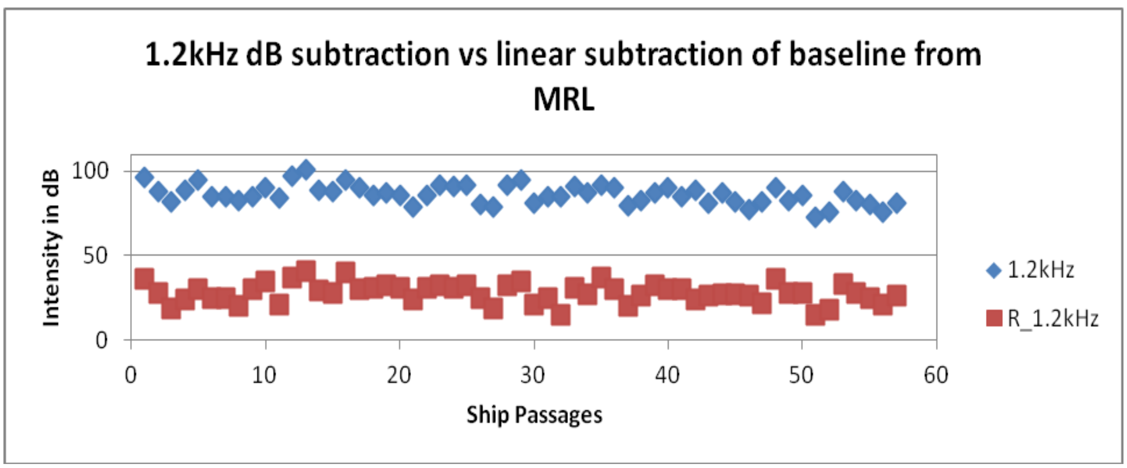


Figure 24: Discrepancy between the two subtraction methods. Red lines are subtraction methods in dB only, blue is with proper conversion. The results show that the correct method for subtraction yields a noise level twice as high as the straight dB subtraction for 1.2kHz.

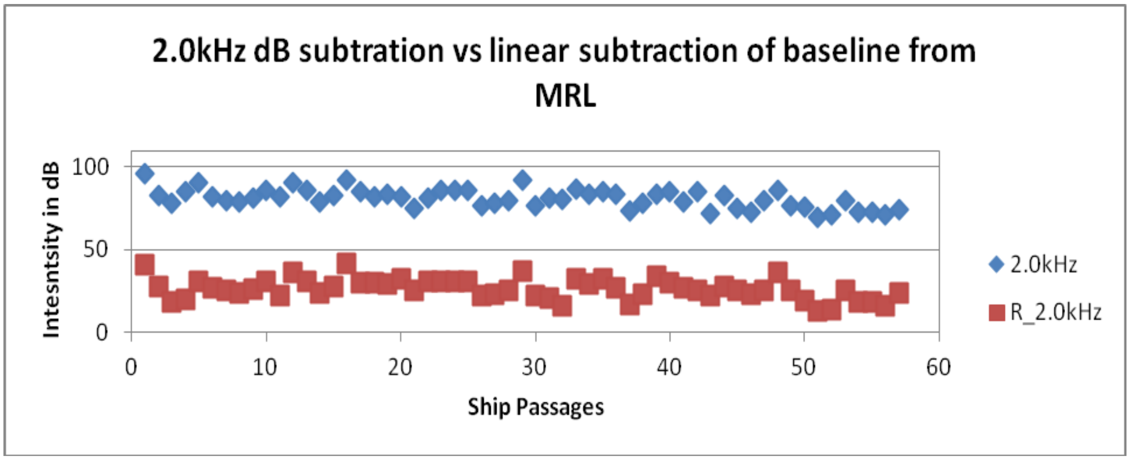


Figure 25: Discrepancy between the two subtraction methods. Red lines are subtraction methods in dB only, blue is with proper conversion. The results show that the correct method for subtraction yields a noise level twice as high as the straight dB subtraction for 2.0kHz.

As previously discussed, dB are logarithmic, so while straight linear subtraction will provide an idea of the relationship between two intensities, it clearly underestimates the true relationship between baseline and MRL. This is important for understanding the potential impact a passing ship has on the marine environment and how it affects an animal's perception of their environment. This type of shift in noise level could obscure communication, homing, or foraging signals important for individual and population survival.

CHAPTER IV

CLICK COUNT ANALYSIS

As discussed in the background section, sperm whales constantly use a variety of click types and patterns for navigation, communication, and foraging. Differences in clicks are associated with different behaviors and can be indicative of activities happening both at the surface and during their prolonged dives. Disruptions to normal behavior from the passage of ships may have a greater effect on fitness if they affect foraging and on social cohesion if they disrupt communication.

To determine whether noise from vessel passages might disrupt normal behavior or communication, clicks were counted for time periods before and after a vessel passed over the buoy. To successfully complete this analysis, multiple preparatory steps were executed.

Part I: Automated Click Counter Calibration

To count clicks during discrete time periods, an automated click counting program, Pamguard, was used. Before using this automatic detector for analysis, the detector was calibrated to ensure results used for time comparisons were accurate. To do this, four time periods were identified for comparison: 1) times without ships or sperm whales; 2) times with ships and no sperm whales; 3) times with sperm whales by no ships; and 4) times with sperm whales and some ships. During the times used for sperm whale clicks with ships present, clicks were still positively identifiable and able to be separated from any vessel noise generated by the distant ship. Audio files were selected based on the notes taken during the hour by hour initial analysis of the full 36 days described in the previous chapter. When audio files matching one of the four time periods were identified, a 10 second sub-sample was created using Adobe Audition CS5.5. The 10 second sub-sample was used because of the manageable number of potential clicks within the sample. Sperm whales click once every 0.5-1 second, on average. The 10 second files were ideal because most files included 3-6 animals clicking at the same time. Generally, these 10 second files contained 90-140 individual clicks, which require significant time per file to process. In order to process enough different samples, 10 seconds samples were ideal for manageable click counts as well as reasonable processing time per file. For files containing clicks, the 10 second sub-sample was entered into a Matlab based program called X-Bat, which is designed for analyzing bioacoustic data such as the audio-files recorded by the buoys. For each sub-sample, a log file was created in X-Bat. Once the audio sub-file loaded into the program, it was reviewed visually for presence of clicks and again aurally to verify whether a ship was present; if a ship was present, whether some of the apparent clicks could actually be vessel noise. Then, each click was individually isolated from the beginning of the click to the end. The start time of each click was logged in the log file for later comparison. Any suspect clicks were isolated and reviewed before being logged to make sure the accuracy rate was as high as possible. A total of 60 sub-samples were reviewed and a total of 2,891 clicks were isolated for comparison. After each sub-sample was analyzed in X-Bat, the same 10 second sample was processed through the Pamguard automatic click detector.

The Pamguard detector was set with a Butterworth bandpass filter from 1-5kHz. While some of the frequencies of interest for noise calculation were below that range, the nearly constant airguns could have confounded the detections if the highpass filter were set lower. In addition, the nearly constant distant ship noise propagation could have also confounded the detector at lower frequencies. Eleven sub-sample files were double processed to test for the best detection threshold for the automated detector. The files were run through the automated detector with a 10dB and 12dB detection threshold and compared with the manual detections logged in X-Bat. For each sample, the precision, recall, and F-score were used to calculate the performance of the detector. The precision reflects the ratio of false (false positive) detections to correct detections; recall reflects the ratio of missed (false negatives) detections to correct detections; F-score then combines the precision and recall to represent the overall ability of the detector to correctly detect clicks.

For each sub-sample, Pamguard creates its own log file containing the start time of each detection. These start times were compared with the start times from the manually isolated X-Bat log files. Start times were considered to be the same if they were within 0.06 seconds of each other. This time relationship was chosen for two major reasons.

The first was that 0.06 seconds was a natural break in the data. Most click alignments were either consistently closer in time than 0.06 seconds or significantly further separated. The other major reason was the measured duration of a click by the program was generally 0.04-0.06. Thus, if the difference in start time was greater than 0.06, it was arguable that the alignment was not for the same click but rather the one click before or after. Because this alignment was so conservative, it could also have increased the number of missed or false detections if the click duration were longer than 0.06 allowing for a larger alignment window. However, this conservative approach increases confidence in the clicks that do align, raising the probability that the automated detection represents an actual click.

For the sub-samples run through the Pamguard detector with the 10dB threshold, there were very few missed detections (high recall) but a large number of false positives (low precision). While it is important for the analysis to detect as many clicks as possible, it was of concern that there were so many false positives. When those same samples were run through the detector with a 12 dB threshold, there were more missed detections (low recall) but very few false positives (high precision). The difficulty was in determining the cause of the false positives: Whether it was more important to detect all the clicks in addition to other signals mistaken for clicks, or whether it was more important to be certain the clicks detected were true detections and miss some of the more ambiguous signals. Because it was impossible to classify the majority of false detections with any certainty, the 12dB threshold was used. This is a more conservative representation of the potential clicks occurring within each time period.

After processing all files through the Pamguard program, the Recall, Precision and F-Score could be calculated for each of the four time periods sampled. For the period where no ships and no clicks were present, all processed files had zero detection, giving a perfect score for that time period and serving as a control for testing the false positives of the automated detector.

Table 6, below, shows all three parameters for times with clicks and no ships, clicks with some ship noise, and times with just ships.

Table 6: Parameters for automatic click counter detection and final scores for each of the three analyses for automatic click detector.

	No Ship	Some Ship	Ships
Precision	87.4%	84.3%	0.4%
Recall	79.1%	77.6%	100.0%
F-score	**83.1%**	**80.8%**	**0.8%**

While calculating those parameters was very straight forward for times with actual clicks, times with false positives but no actual clicks provided a challenge for calculations since the formula requires the number of correct detections in both the numerator and denominator. In order to compensate for this, the assumption was made that one click was present and correctly detected for all time periods. This allowed the same formula to be used for all time periods and the calculation for a correction factor.

Part II: Statistical Analysis of Click Counts Relative to Ship Passages

Once the correction factors were calculated, it was possible to start mapping the ship passages in terms of clicks per .wav file. For the initial characterization of ship passages described in the previous chapter, 56 instances were identified. These 56 were cross-referenced with the data sheets containing hour by hour information. Those with specific notations for sperm whale groups were flagged as potential times for click analysis. When the initial notations were made for the hour by hour analysis, the first .wav file wherein the presence of the ship was obvious was recorded as the 'start' of the arrival of the ship. The file wherein the ship was the loudest was noted as the file for the closest point of approach (CPA), or the time when the ship was closest to being overhead for that ship. For each ship passage, a minimum of 13 .wav files were processed through Pamguard for click detections. Ideally, five time samples were needed for the click count analysis: 35 minutes before the ship CPA; 17.5 minutes before CPA; ship CPA; 17.5 minutes after CPA; and 35 minutes after CPA. Those time periods were selected because the .wav files are 5 minutes and 50 seconds long and in general, 35 minutes is the largest buffer between ship passages (determined from the data).

While this selection of time periods appears straight forward, ship passages were not always clearly defined nor were they independent of each other. As seen in the initial analysis for ship passage metrics, multiple ship passages often occurred consecutively and often without a complete separation between departure of one and arrival of the next. This same overlap was present in the click analysis data as well. While ideally, the 5 time periods were measured, often passages were not completely detected because of the arrival of another ship. The figure below, Figure 26), shows three different ship passage scenarios. The first is a single, well defined ship passage; the second shows multiple ship passages that are discernible; the third shows a much less well defined passage.

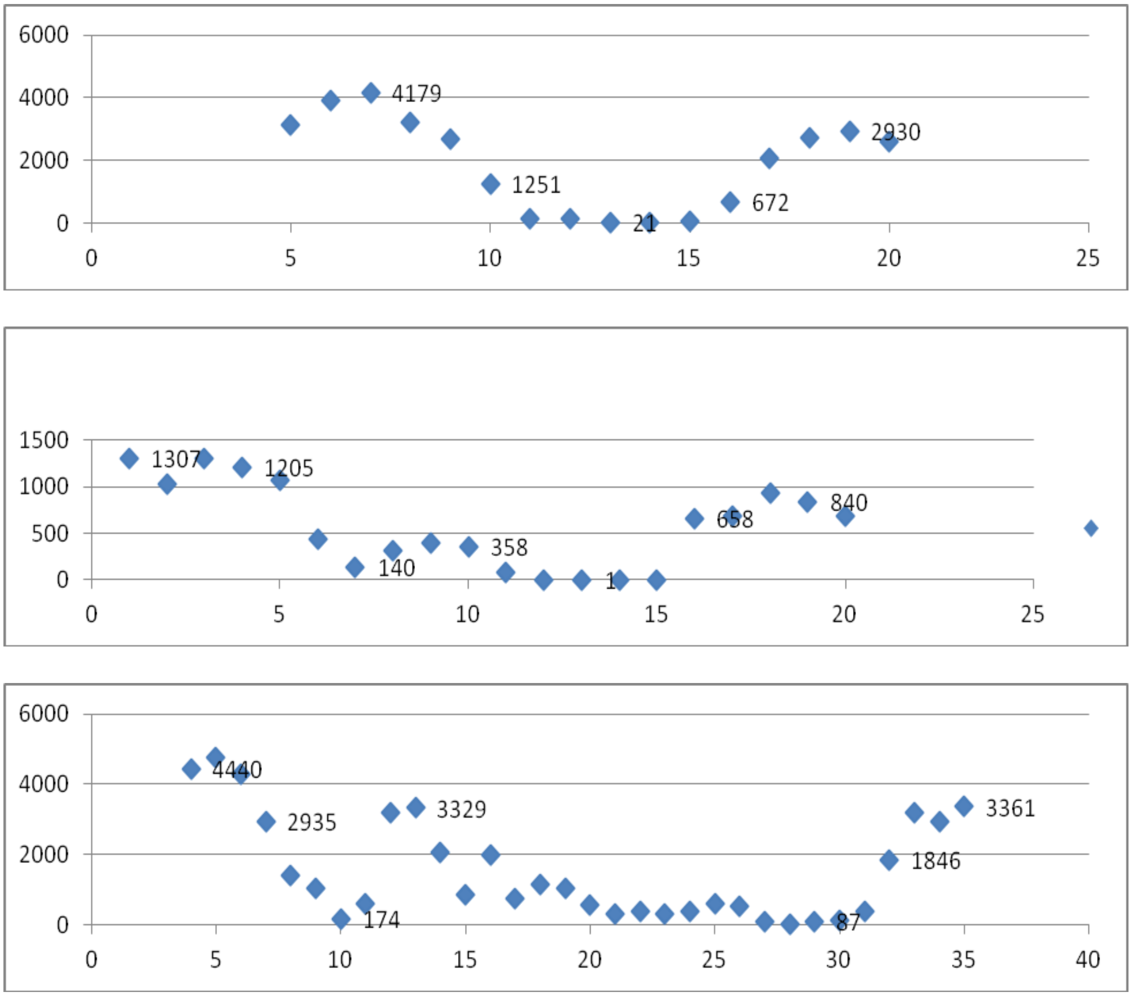


Figure 26: Examples of Ship Passages showing 1-ship, 2-ships, and Multiple-ships. Each blue point represents the number of clicks in a 5:49sec sound file.

While the pattern of arrival and departure of the ships is obvious in each graph, it is apparent that there is no typical number of clicks that serve as a baseline for “pre-ship” or “post-ship.” Because of this variability, each .wav file was also aurally and visually reviewed to verify the presence of sperm whale clicks, the arrival, CPA, and departure of each ship. This became increasingly important when multiple ships passed consecutively since vessel noise often confounded the automated detector and were misidentified as clicks.

Each ship passage was named for the day and hour the first ship started to arrive. Once the CPA for the first ship passage was identified, time periods preceding it were processed out for at least six .wav files (representing 35 minutes). The files were then processed moving forward and while, ideally, a single ship passage was identified, files were continuously processed until an end point of any of the subsequent ship passages could be reached. As is visible from the above examples, much of the time, these 5-point ship passages did not exist. Often, the two times before CPA were detectible, but not the times after if another ship arrival overlapped with the initial ship. There were often too many ships too close together for the kind of separation needed to isolate 5 points for each ship passage. To deal with this, passages were broken into before and after and the most points surrounding each CPA were identified. The original plan for analysis was to divide the passages into those with single ships or multiple ships, but there were so few times where an individual passage was identifiable, the data were grouped by time period. Those click counts for times 35 minutes before CPA were grouped together; those 17.5 minutes before CPA were grouped together, etc. These 5 groups were then compared statistically for difference of means. The final number of samples per time period and average clicks per time period are provided in the table and figure below

[Table 7; Figure 27)]. The table shows the average number of clicks per time period in graphical form.

Table 7: Total number of sound files analyzed per time interval and the average number of clicks in each file.

Time interval	35 Min Before	17.5 Min Before	CPA	17.5 Min After	35 Min After
Samples analyzed	37	41	43	38	31
Average number of clicks	2132.14	1348.23	15.60	1078.53	1645.96

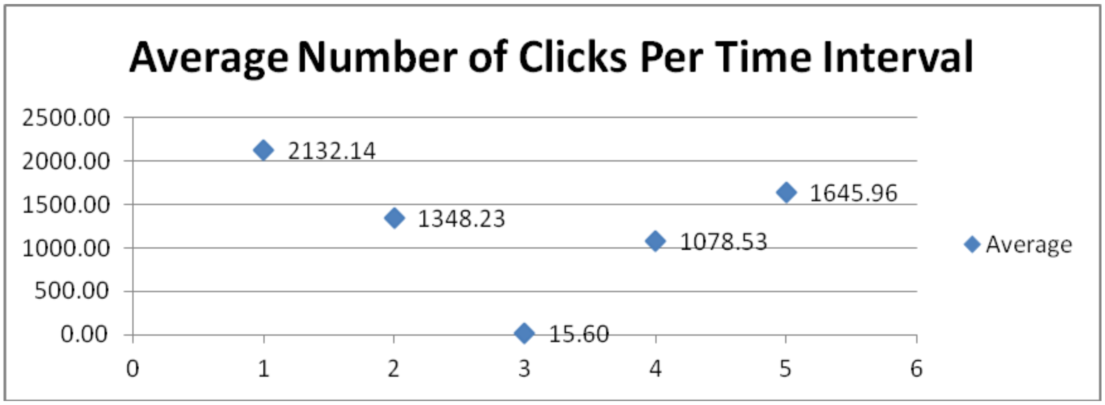


Figure 27: Average number of clicks per sound file sample per time interval.

Click averages for each time period were compared non-parametrically using the Mann-Whitney U test for difference of means for independent samples. The complete results of the statistics including P values are presented in Table 8, below. One particularly important relationship to notice occurs as the ship arrives. There is a significant decrease in the number of clicks between 35 and 17.5 minutes by 36.67% before the CPA of the ship. There are also significantly fewer clicks detected 35 minutes after the ship passes than before, a reduction of 22.8%. The only time period comparison that was not statistically significantly different was between 17.5 minutes before and 17.5 minutes after CPA.

Table 8: Statistical results for non-parametric comparisons of average click means between time intervals or arrival and departure of ships.

Comparison	% Difference	P value	Significantly different?
35 min before vs. 17.5 min before	36.67%	0.001	Yes (99% confidence)
17.5 min before vs. CPA	98.80%	0	Yes (99% confidence)
17.5 min after vs. CPA	98.50%	0	Yes (99% confidence)
35 min after vs. 17.5 min after	34.47%	0.004	Yes (99% confidence)
35 min before vs. 35 min after	22.80%	0.015	Yes (95% confidence)
17.5 min before vs. 17.5 min after	20.00%	0.148	No

These results indicate that as a ship approaches, one of a few events or combination of events may be occurring. The first and most obvious is that sperm whales are leaving the area. They are not only leaving, they are leaving preemptively before the ship actually arrives. The second is that because of the low frequency limitations of the data, the ship noise is radiating far from the ship at noise levels that are able to obscure the clicks by raising the noise floor enough that the detector cannot pick them up. Based on the correction factor for correct detections, there is still strong detection ability for clicks during times of approaching ships. This was specifically tested and reflected in the "ships and clicks" time period correction calculation. Other possibilities include a cessation of clicks from animals nearby but not a movement away from the area, surfacing of animals as part of natural dive patterns, or avoidance mechanisms. There is no way to tell, from the buoy data alone, which of these scenarios is occurring or whether it is a combination of the possibilities. What is clear from the results is the definite indication that there is some type of behavioral change or effect (masking) that occurs in the presence of vessel traffic and that this effect needs to be studied more closely.

Part III: Click Amplitude Comparison Analysis

Click number is an important indicator for group size and presence or absence of whales. Changes in clicks, as discussed, could indicate a number of behavioral changes, either natural or related to anthropogenic disturbance. Click amplitude or loudness is also a component that is measurable. Click amplitude depends on many factors. Since the buoy is only able to measure received click amplitude, factors such as animal distance, orientation, and depth could all be factors. Additionally, ambient noise levels and transmission parameters (depth, density, absorption, spreading, etc.) can also affect the received level. Lastly, the detector used has a shifting noise baseline calculation. The detection threshold is always 12dB above the noise floor. Increases in received noise may cause lower amplitude clicks to be missed in a noisier environment (potential indicator for masking; however, missed clicks are not necessarily masked).

For example, for humans in every day conversation, when a train comes through an area, some people will chose to leave that area and continue their conversations elsewhere; some will stay and either halt their conversation until the train passes or speak louder to try to overcome the noise from the train. Based on the results of the click analysis, it appears that some whales may be leaving the area as the ship approaches or they stop clicking. But for those who remain in the area and are still audible above the noise, is there any evidence that they may be changing their clicks to compensate for the additional noise? To investigate this question, the verified click amplitudes from the 10 second calibration sub-samples during the “no ship” and “some ship” periods were compared. Because these sets were used for the calibration, each of these clicks had to be aurally and visually verified and time aligned as previously discussed so the likelihood that these are false detections is very small.

For the analysis, eleven files from both “no ship” and “some ship” were used. A total of 1,557 click amplitudes were isolated: 776 from “no ship” files and 781 from “some ship” files. These two groups were compared statistically using a Mann-Whitney U non-parametric test for comparison of means for independent samples. The results of the statistical test show a statistically significant difference of means (P= 0.002) and are shown in Table 9, as well as graphically inFigure 28: Box and whisker plot showing separation of means for average click amplitudes comparing times with ships to times without..

Table 9: General statistics for click amplitudes from samples without ships and with some ship noise present.

	N	Mean	95% Upper Bound	95% Lower Bound	Standard Deviation
No ship	776	159.42	159.75	159.1	4.645
Some Ship	781	160.32	160.67	159.97	4.947

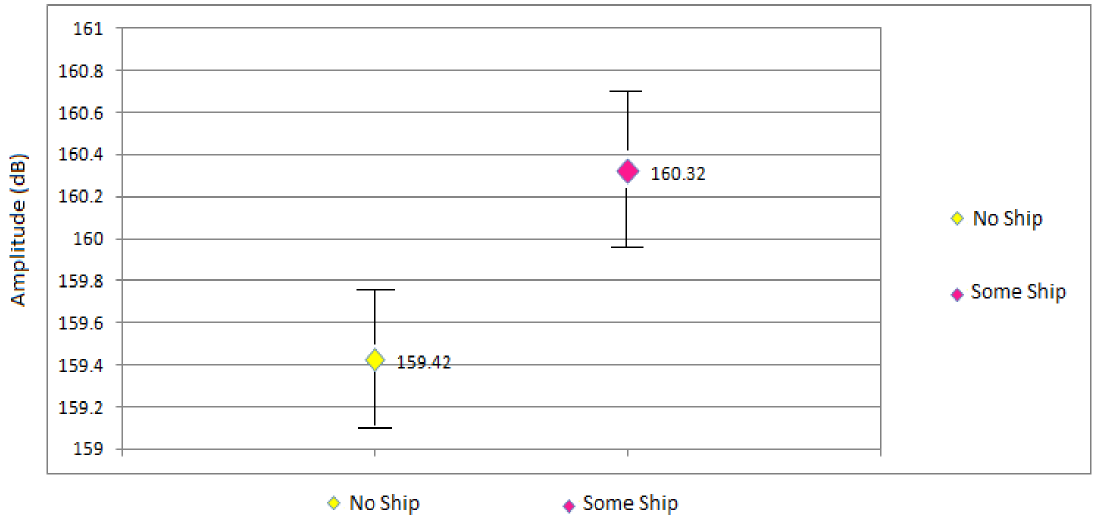


Figure 28: Box and whisker plot showing separation of means for average click amplitudes comparing times with ships to times without.

In this case, while statistical differences in the relationship may be significant, practically, they may not. Another way to evaluate this relationship is by looking at the distribution of amplitudes in a histogram. If the two data sets are the same, the distributions should overlap. The first two figures [Figure 29) and Figure 30)] show the respective distributions separately. Figure 31) shows the distributions side by side while Figure 32) shows where the major differences in distribution lie.

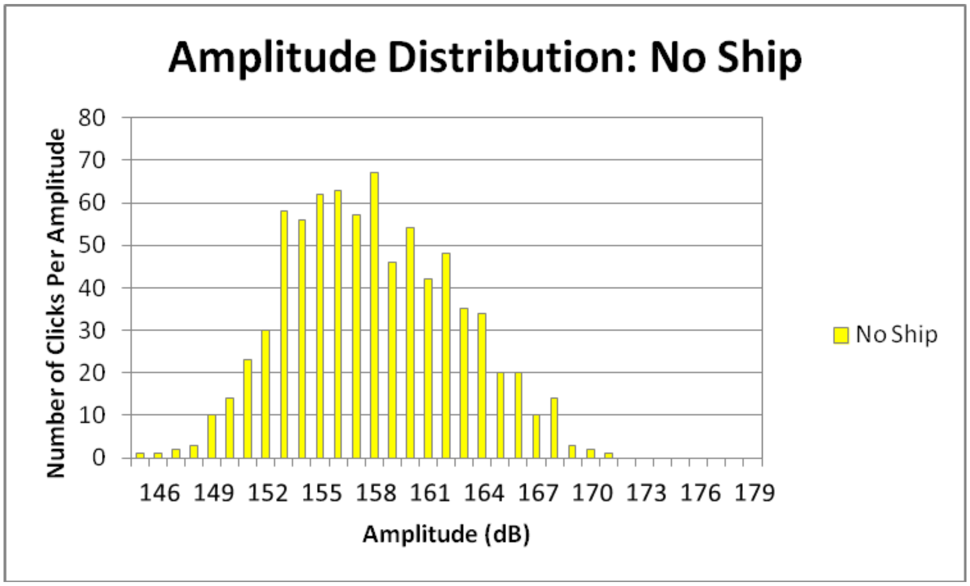


Figure 29: Amplitude distribution of clicks for times without ships present.

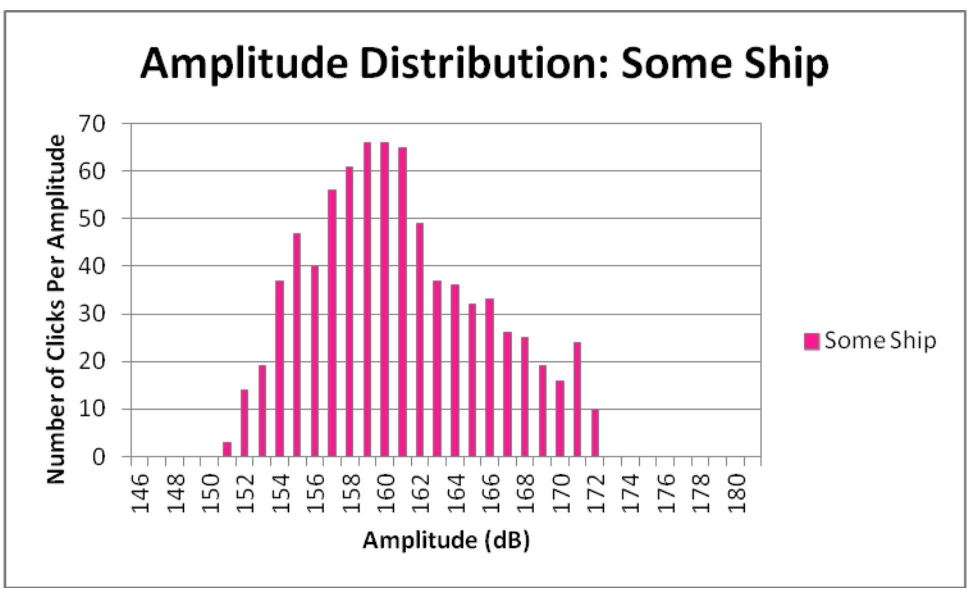


Figure 30: Amplitude distribution of clicks for times with some ships present.

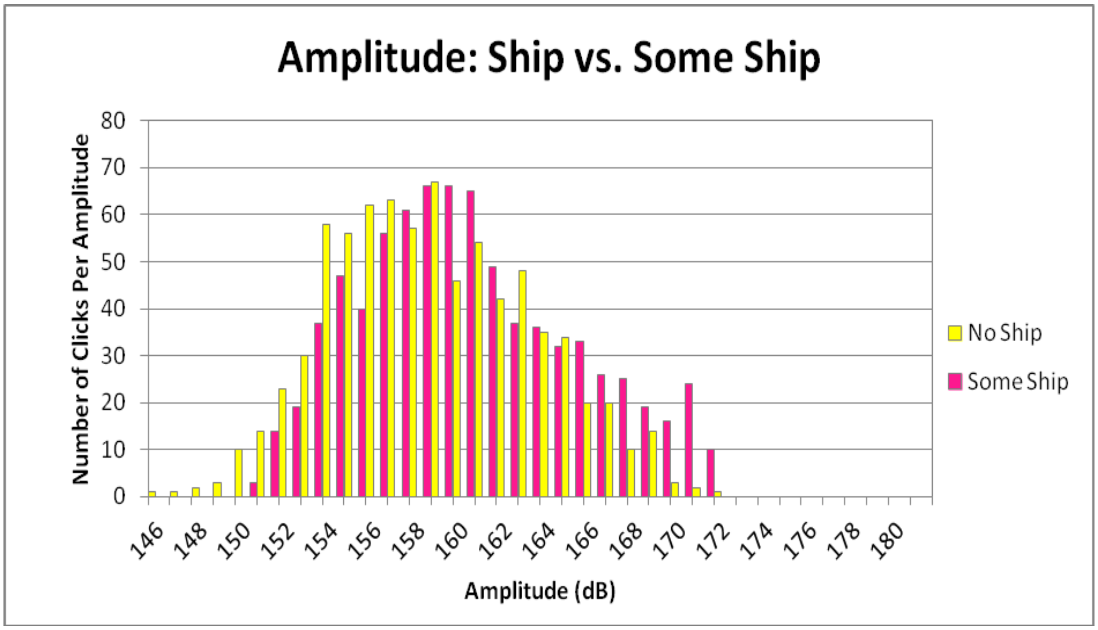


Figure 31: Histogram comparing distribution of click amplitudes between times with some ship and times without.

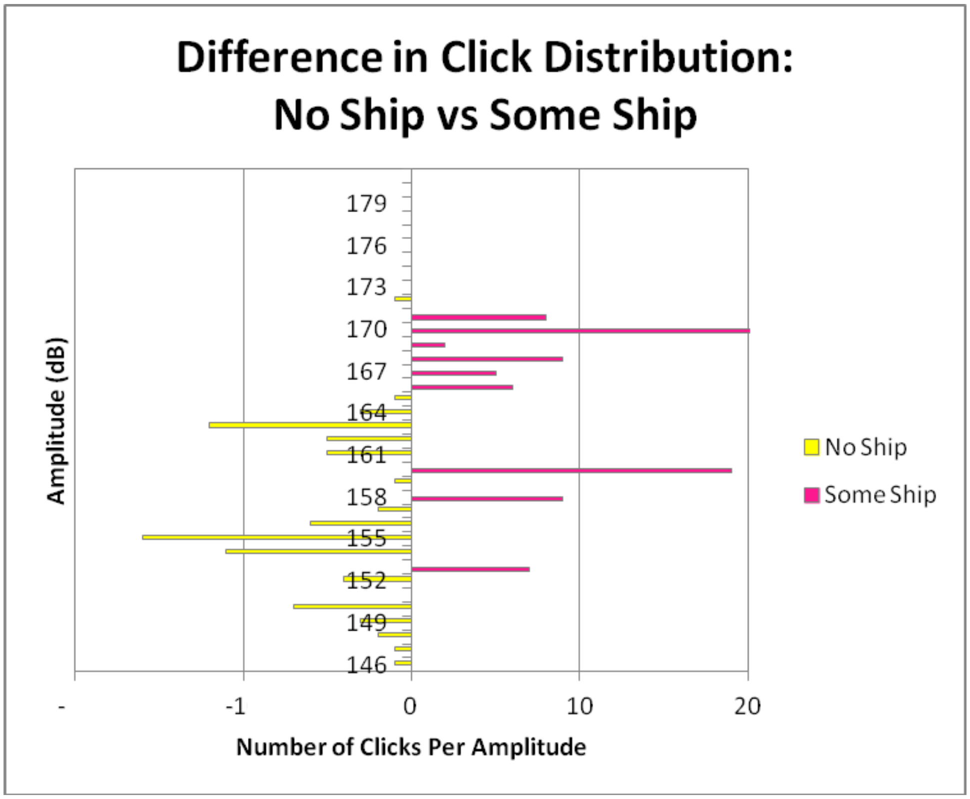


Figure 32: Separation chart showing number of clicks per amplitude bin (in dB) for times with ships and times without.

From this last figure [Figure 32)], the offset in the two distributions can be seen. Amplitudes during the period "no ship" are more heavily distributed below 160dB. There is a large overlap in the two distributions between 160dB and 165dB, but the difference in distribution for "some ship" is more heavily weighted towards amplitudes greater than 165dB. These results are based on a very small subset of data and are subject to a number of potential confounding factors as discussed previously. Even if the moving detection threshold removed some of the clicks at lower amplitudes from the "some ship" period, clicks at higher amplitudes would not have been affected or removed from the "no ship" time period. Confidence in the results of this analysis would be improved by increasing the size of the data set. This is difficult because although a correction factor has been calculated for overall click counts, which individual clicks are correctly detected needs to be assessed by direct comparison. This may be something that could be programmed into a separate analysis tool which would allow more rapid alignment and verification of correct detections. However, with the limited data set available, the results are certainly interesting and suggest that there may be an increase in click amplitude as ships approach. This is supported by the statistical tests, although in this case, the differences in distribution may be more applicable than the statistics alone.

CHAPTER V

DISCUSSION OF DATA ANALYSIS

The data analysis presented in these last chapters can be summarized by a few basic statements. Vessels traffic in the GoM is very loud, so loud that as a vessel passes over the buoy, other natural environmental noise becomes insignificant. As these vessels approach, there is a significant reduction in the number of sperm whale clicks detected. There is a distinct decrease in clicks persisting even a half hour after the ship passes over the buoy when compared to a half hour before. Lastly, there appears to be evidence suggesting that whales that do continue to click as a ship approaches and are clicking at higher amplitude (louder volume) which may indicate another example of the Lombard Effect in marine mammal communication. The Lombard effect or is the involuntary tendency of speakers to increase their vocal effort when speaking in loud noise to enhance the audibility of their voice (Lane and Tranel, 1971).While these statements are interesting, the implications of these results may not be immediately apparent.

For statements such as these, it is imperative to discuss them in a context where their importance is apparent. Much of the analysis was necessary for establishing background relationships among the data: for example, looking at ambient noise levels and determining baseline statistical relationships between times with ships and times without. The set of analyses focusing on metrics of ship passages were designed to clarify the type of environment that is created when a vessel passes. The two most important metrics for understanding impacts on the environment were the vessel passage time and the duration of the Maximum Received Level (MRL). This type of information is important for understanding short term noise variations and their presence relative to short term sperm whale behavior such as diving, feeding, socializing, or resting.

The majority of the ship passage times fall between 20 and 50 minutes with an average of 29 minutes. A typical sperm whale dive is approximately 40-45 minutes, with 8-10 minutes spent resting on the surface. On average, the duration of MRL was 23% of the total ship transit time. This means that on average, 60-75% of a dive cycle is dominated by ship noise and when more than one ship passes consecutively, it can extend into multiple dive cycles. The major and most apparent impact of this type of noise overlap is the potential inability of foraging individuals to hear their own signals necessary to successfully locate and capture prey. This type of recurring signal and noise overlap can have other impacts on communication which is particularly important for a species as socially cohesive as sperm whales, as noted below. While adult sperm whales use loud, broad band signals, very young juveniles that cannot yet make the deep foraging dives use much lower frequency clicks. These clicks are directly within the noise frequencies measured in this study where nearby vessel noise completely overwhelms all other environmental noise, including biological signals. The potential exists for these juvenile clicks to work as a homing mechanism for diving mothers to be able to relocate their young; vessels which obscure this signal make small group cohesion more difficult and separation more likely.

Sperm whales are also highly social and have large gatherings of multiple groups which may convene for activities such as mating and which incorporate rhythmic click patterns called codas into their group socialization. Even if ship presence does not completely obscure the complete signal -- for example, as ships approach the area -- reductions in click detection by 36% means that one out of every three clicks might not be detected. While this wouldn't make a conversation impossible, missing one out of three words might mean hearing nonsense or irrelevant detail and thus, misinterpreting the message. With a complex communication language completely reliant on transmission and reception of clicks and click patterns, any missing information could mean the message becomes ambiguous resulting in erroneous reactions. A good example of this might be the transmission and reception of clangs which are low frequency clicks produced by males and thought to be linked with sexual selection (as previously mentioned). These clangs are directly within the frequency range shown to be influenced by near field shipping (ships that pass very closely) which means that reception of these clicks becomes based more on presence or absence of ships. If these clangs are truly indicators for fitness and all or a portion of the signal is obscured or misinterpreted, the ability for females to make choices based on evolutionary methods, such as honest indicators, may not be valid. For a population considered to be endangered, reproduction and successful recruitment of juveniles into the adult population are extremely important. That process is based entirely on healthy, fit parents: adequate protection and rearing from the mother as well as the ability to successfully forage and survive to maturity. These nurturing strategies are all potentially compromised by shipping which ensonifies their ecological environment for up to 60% of their life based on the average time it takes a ship to pass.

Research analysis needs to focus on measureable changes and actual results to identify both the successes of the project as well as the short-comings. The second portion of the analysis on click counts and characteristics provides important results that help develop the next set of questions. As presented in the results of the click counts, there is a significant decrease in the number of detectable clicks as vessels approach the buoy; there is a complete lack of detectable clicks when the ship is loudest, presumably the closest point of approach (CPA); additionally, the number of clicks 35 minutes after the ship passes is significantly lower than the number of clicks detected 35 minutes before the ship's CPA. Because there is no data to prove what happened during those times, several possibilities exist. The most obvious for the decrease or absence of clicks is that the increase in noise from the ship overwhelmed the clicks so they could not be heard. This only holds true when the assumptions that the whales stayed in the area and continued clicking throughout the ship passage are met. However, whales may have left the area and also may have stopped clicking, both of which would influence the number of clicks that would be there to detect.

Measureable changes in click amplitude were also possible. The results from the analysis of click amplitudes between times with no ship noise and times with some ship noise showed that there was a shift in the distribution of click amplitude to higher amplitude clicks when ship noise was present. This suggests that while fewer clicks may be detected with approaching ships, clicks detected are louder, suggesting that the sperm whales that do stay in the area with ships may also be adjusting the loudness of their clicks to compensate for the increase in background noise. Combining this information with the results of the click counts provides a new hypothesis for future work: as ships approach, different coping mechanisms are used by sperm whales to overcome the influence of ship noise on communication and foraging. Some of the sperm whales in the area may leave or stop clicking as a result, while those that stay click at higher amplitudes in an effort to increase the signal to noise ratio and be heard. There are multiple unknowns in this situation that need to be resolved to test this hypothesis, the most integral of which is determining the source level for sperm whale clicks. This determination would allow comparisons of amplitude during quiet times and noisy times. It would also potentially help determine the range of the animal based on the received level of the click which, in turn, might answer the question of whether whales are moving away as a ship approaches. To resolve these unknowns, research using alternate methods is needed. These methods are discussed further in the final chapter.

CHAPTER VI

REVIEW OF MARINE MAMMAL RESPONSE TO NOISE

Although marine noise perturbations from shipping are often overlooked in implementing effective management strategies, research into this subject is not new. Studies have shown that when exposed to noise, there are a variety of reactions and behavioral changes that could occur. Most obvious is that whales can leave the area. But that may not be energy efficient if the food and the social networks they seek are within the area dominated by pervasive vessel traffic. One of the major disadvantages to remaining in an area of increased noise, when communicating acoustically, is not being able to hear oneself or others [Figure 33)]. The introduction of noise can obscure signals or cause these signals to become "lost" in the noise. This is a serious issue for animals who communicate, navigate, and forage based on hearing their own calls or those of their consorts. To combat this, there are a number of characteristics within a signal or call that can be modified such as length, frequency, or amplitude. Sometimes, more than one of these modifications is used. If the noise input is within a frequency band, modulating the frequency of a call or part of a call might remove the conflict. Lengthening a call could differentiate it from the vessel noise, as can changing the calling interval. Calling more often increases the chances of being heard in a lull, calling less frequently may enable calling for a longer overall period. Alternatively, increasing the amplitude (energy within the call, or volume) could also increase the signal detectability to a level above the noise. All of these call modulation modifications could also affect energy consumption.

By spending a greater time communicating or longer times foraging with less time resting, the balance between energy consumed and energy used [input and output] could change resulting in a decrease of long-term fitness of individuals.

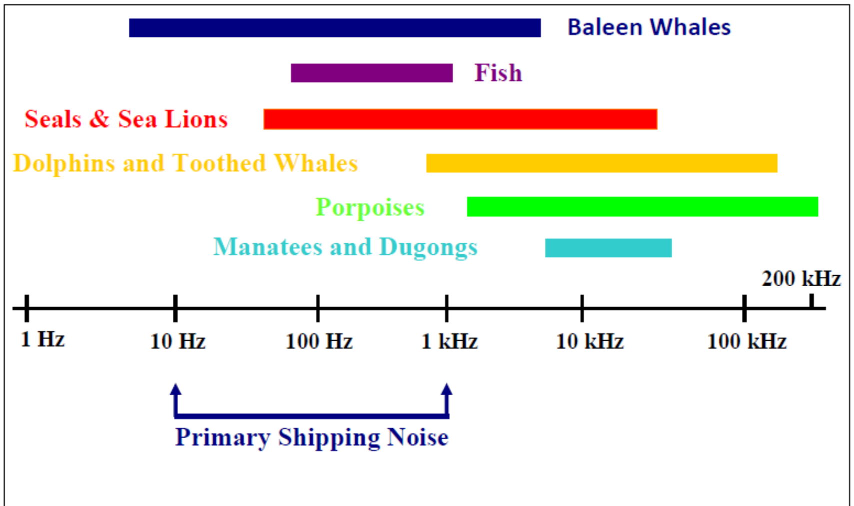


Figure 2. Frequency Relationships Between Marine Animal Sounds and Sounds from Shipping. Figure courtesy of B. Southall, NMFS/NOAA

Figure 33: Overlap in frequency use between primary shipping noise and marine mammals (Okeanos: Foundation for the Sea 2008).

Much of the concern arose from whale strandings in association with military activities (Jasney 2005). These impacts have been discussed at length by National Research Council (NRC) and National Resource Defense Council documents as well as in legal proceedings (for further discussion of this please see: National Research Council, 2003; Inkelas, 2005; and Jasny, 2005). In response to this, new research objectives were called for by scientists and regulators, some of which included controlled exposure experiments with LFA (low frequency active) sonar. These experiments were designed to monitor any behavioral reactions to sonar in the area including acoustic changes. In 2000, Miller et al. found, through controlled exposure experiments, that humpback whales lengthened their song during LFA playback experiments. Humpback songs were measured to be 29% longer during the playbacks which resulted from longer themes within the normal call structure. More recent work (Dunlop et al., 2010) with humpbacks and ambient noise interactions has shown a different kind of reaction. This study compared acoustic signals with surface active signals (tail slaps, breach, pectoral slaps) under increasing wind and wave conditions (which are directly related to increases in ambient noise). These comparisons showed an increase in surface active behaviors as wind speed increased. This positive relationship indicates that whales prefer surface communication over vocal communication as ambient noise levels increase (thus, the underwater environment gets louder). These types of relationships need to be further investigated to see if the pattern persists when increases in ambient noise are due to anthropogenic inputs, like vessel noise, instead of noise from wind and waves.

North Atlantic right whales are exposed to large numbers of ship passages along the east coast of the United States and Canada. Multiple shipping routes around Nova Scotia, the Boston Harbor, and the south-east coast of Georgia and Florida, for example, contribute to noise disturbance by large, constant vessel traffic. This results in an opportunity to observe behavioral and acoustic responses to the presence of vessel traffic. A study in 2007 (Parks and Clark, 2007), found that right whales adjust several features of their calling in the presence of ships. First, they increased the fundamental frequency of their calls. This was achieved by increasing the minimum frequency of their calls with an overall shift increase of 2/3 octave. This may be a mechanism to reduce overlap within the bandwidth of the shipping noise. Over time, there may be a more permanent shift in frequency. In addition, there was also a reduced call rate. Amplitude was not measured, but, as discussed in the paper, if amplitude per call increases, so does effort per call, which could account for the overall reduction in call rate. A later paper by Parks et al. (2009) found that, based on the up-calls, there was no response in dB to increased noise but that there remained a shift in frequency of calls indicating that the whales may be responding to the peak frequency of the noise rather than the sound intensity level. Most recently, the question of amplitude shifts was addressed (Parks et al., 2011) through measuring received levels of ‘up calls’ from archival suction cup tags (DTAG) placed on 11 whales in the Bay of Fundy. The analysis shows a linear relationship between increase in received level and increase in noise level. These shifts were short term responses to increases in noise level. These findings combined with earlier studies show that noise from passing vessels not only triggers changes in fundamental frequency but also amplitude for North Atlantic right whale up-calls and could be a serious factor in behavioral changes affecting communication within the population.

In the North Pacific, a similar situation has been observed during the interactions of killer whales and vessels. Not unlike humpback whales, killer whales were observed changing the duration of their calls in the presence of boat traffic (Foote et al., 2004). An increase of 15% in call duration was recorded when ships were present. Interestingly, it seems that there may be a threshold level for this increase; that vessel noise must reach a certain sound intensity level before this increase in call length occurs. This suggests some tolerance of noise in the environment, or at least the ability to compensate in other ways before making detectible changes to the calls. A later study in the same area further expanded on these findings. Holt et al. (2009) found that there is evidence to suggest an increase in call amplitude of 1dB for every 1dB increase in noise. This confirms evidence of the Lombard effect in marine mammals in response to noise.

Belugas in the St Lawrence Estuary were also evaluated for reactions to anthropogenic noise (Scheifele et al., 2005). Vocalizations from subgroups of the 700 belugas in the upper estuary were recorded during the summer time over 6 years. Vocalizations from several different subsets of time were all statistically compared with significant results: Times with ship source anthropogenic noise were compared with times without the noise before, during, and after vessel passages. While changes in frequency and call type have been previously discussed, this paper shows that changes to source level are also apparent in the presence of ship passages. These findings were encompassed several years and at several different locations within the St Lawrence Estuary with differing noise input levels. Based on these results, human generated noise has a measureable effect on the vocal behavior of beluga whales which demonstrates the Lombard Effect across species and geographic locations.

This pattern of change is not only found in whales and dolphins, studies on manatee vocalizations have found a similar pattern. A study comparing manatee vocalizations under different behavioral states and social structures in response to anthropogenic noise yielded complementary results showing continuity of the effect of noise across location and species (Miksis-Olds and Tyack, 2009). This study examined the use of squeaks and chirps in social situations in response to the presence of anthropogenic noise. The usage of calls differed depending on presence or absence of calves; however, the general pattern showed significant changes in vocalization effort such as decreases in vocalization rate, increases in duration, decreasing peak frequencies, or alterations in source levels in response to noise levels. Additionally, effort and call interval decreased in the presence of ship noise indicating that cessation of calls may mean that manatees are waiting for a lull in the noise instead of expending the energy necessary to communicate in a noisy environment. Changes in call duration and interval are observed in several species, once again tying the problem to increasing noise and not just an individual's isolated response to noise.

Table 10: Summary of noise effects discussed in this chapter.

Marine Mammal Response to Noise						
	Changes in Call:					
Species:	Frequency (Hz)	Duration	Amplitude	Repetition	Type	Over all Effect
Humpback whales		Increased				Calls are longer overall; Increased surface activity and decreased acoustic activity
North Atlantic right whales	Increase		Increased	Reduced		Combined results show increases in fundamental frequency and amplitude as well as a decreased call rate in presence of
Killer whales		Increased	Increased			Increase in call duration as well as amplitude in presence of ships
Beluga whales			Increased			Source level of Beluga calls increases in presence of ships
Manatees		Increased	Increased	Reduced	Alterations	Changes in call type depended on presence of calves. All repetition decreased and stopped in some cases while duration and amplitude increased in presence of ships
Cuvier's beaked whales						Alterations in diving and foraging behavior

The last of these examples are cuvier's beaked whales. Another ship noise exposure experiment with tagged whales in 2006 (Soto et al., 2006) showed that beaked whales change their diving and foraging behavior in the presence of vessel noise. What is particularly interesting about this study is that beaked whales use high frequency clicks for communication and foraging where vessel traffic noise is generally thought of as very low frequency, so there should be very little overlap between the frequency range beaked whales use and ships use. A study by Arveson and Venditis (2000) showed that radiated noise from a large cargo ship actually extended far above what is generally considered low frequency and was measured at a source level of 150 dB re 1µpa at 1m at 30kHz. Another interesting point raised by the article (Soto et al., 2006) on beaked whales discusses a reduction in detectible range with an increase in noise. An increase of 12dB of noise within the click bandwith reduces the range of echolocation (Au, 1993). The range of sonar detection decreases by 42% where the range for communication decreases by 18%.

This same issue of communication space was raised in response to small vessel noise in coastal deep water habitats (Jensen et al., 2009). Studies of noise impacts on bottlenose dolphins as well as pilot whales were carried out using archival recording tags designed to document noise exposure on free swimming animals; ultimately measuring decreases in communication space as vessels increased their speed to greater than 5knts. Their results suggest that decreases of 26% in communication range occur when slow moving vessels (5 knots) pass within 50m of dolphin groups. For pilot whales, there is an estimated decrease of 56% communication range over deeper waters with generally lower baseline noise levels for ships at the same range and speed. While the study does not demonstrate changes in vocalizations, it does show the direct impact passing vessels have on the range over which marine mammals can communicate. This loss of communication range may be a precursor or co-occurring factor driving changes in vocalization characteristics as discussed above.

The results discussed in the last chapter further show that this reaction phenomena are not limited to baleen whales, or odontocetes, or dolphins or manatees. It is not limited to the Atlantic, Pacific, Gulf of Mexico, offshore, or onshore. Noise pollution from ships and vessel traffic is pervasive across all species and geographic locations. It has been identified in the scientific literature as being responsible not only for changes in behavior but in communication. With all this evidence identifying the problem, a proper analysis of the existing legal and management framework for limiting this type of anthropogenic perturbation on marine mammals is imperative. Only through an assessment of current regulation can gaps be identified and replaced with a proactive approach to the management of vessel created ocean noise.

CHAPTER VII

FRAMEWORK FOR THE MANAGEMENT OF MARINE NOISE POLLUTION

Pollution in the marine environment has been addressed in many ways federally, regionally, and internationally. Some frameworks address the issue from a commercial side in an attempt to regulate areas such as maritime safety or ocean dumping, while others focus on conservation and maintaining environmental integrity through protection of resources. More recently, marine acoustic pollution has become an important issue particularly in light of a number of incidences involving the death of marine mammals. There have since been vague attempts to articulate a solution to this problem through suggested policies dictating the type of sound sources to which marine organisms and environments, in general, can be exposed.

Because the focus of this discussion is on current laws and conventions that could be used to establish effective management, this response will focus only on those laws where the architecture would support future progress in the direction of more stringent regulation. Those without this framework are not and would not be effectively included in new guidelines and so will not be directly discussed.

Regional Framework for Noise Pollution Management

While an overriding patchwork quilt of current federal and regional agreements, international conventions and/or treaties may not provide the most effective strategy to reduce or abate vessel noise pollution in the long run, current regional conventions and agreements do present areas where it would be possible to combine efforts and base future direction on cooperative agreements where overlap between regions already exists. Three of these agreements are the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention), the Agreement on the Conservation of Small Cetaceans in the Baltic and North Seas (ASCOBANS), and the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS). Each of these has established a framework for the protection of marine resources, marine mammals (cetaceans) and/or ecosystem and biological diversity.

The OSPAR convention does not directly mention anthropogenic noise as a pollutant in its original language. Its intent was to directly address pollution from land sources as well as the broader task of protecting and conserving biological ecosystems. However, a report in 2000 by the OSPAR Commission addresses concerns about human activities, more specifically, noise from wind power generation, and acknowledges additional concerns about noise impacts on marine mammals but not with regard to impacts from military, oil and gas, or shipping.

In its original language as well as in subsequent Commission reports the convention does focus on a critical concept – the application of the precautionary approach or principle. This approach governs the ways activities which present a potential threat to the environment should be pursued. The precautionary principle has been referenced in dealing with the protection of the marine environment. Article 2 of the OSPAR convention states: The precautionary principle, by virtue of which preventive measures are to be taken when there are reasonable grounds for concern that substances or energy introduced, directly or indirectly, into the marine environment may bring about hazards to human health, harm living resources and marine ecosystems, damage amenities or interfere with other legitimate uses of the sea, even when there is no conclusive evidence of a causal relationship between the inputs and the effects (Convention for the Protection of the Marine Environment of the North-east Atlantic, Art. 2, Sept. 22, 1992, 32 I.L.M. 1069 [1993]. The burden falls on the proponents of the activity to prove that their actions will not have unacceptable impacts on the environment for the activity to continue. Additionally, the OSPAR specifically includes the goal of conservation of ecosystems and biological diversity in its 1992 form (McCarthy, 2004).

ACCOBAMS, likewise, is concerned with the protection of cetaceans from pollution. However, noise is also not addressed in this agreement. A later report to the Secretariat in 2002 presents information on noise disturbances to cetaceans and proposes several mitigations measures. Such measures include quieting technology for props, reducing speed, insulating against hull vibration, adjusting seasonal and daily timing of activities for minimum exposure, as well as implementing monitoring plans during activities like seismic surveys. However, the report was designed only to be informational and contains neither rules nor guidelines to prevent these disturbances or enforcement of these mitigation methods (Di Sciara, 2002).

The same type of framework is found in the ASCOBANS agreement on small cetaceans; however, the agreement includes specific language for addressing the affects of noise on cetaceans. The agreement provides recommendations for the seismic, military, and commercial shipping industries and outlines measures to be taken that would reduce the impact. While definitive measures are suggested for seismic and military activities, only recommendations for further research are made in reference to impacts of shipping and vessel traffic [Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas, March 17, 1992]. Unfortunately, while ASCOBANS makes strong recommendations, it lacks obligations, implementation measures for, and enforcement of those recommendations. Like the other three, it functions as a cooperative means to conduct research and propose management strategies, but is remiss in providing concrete guidelines or plans for action.

Two regional agreements on the Antarctic and Arctic areas are also valuable starting places for regional management practices. The 1991 Environmental Protocol imposes stringent standards on activities having more than a minor or transitory impact; it calls on the parties to limit adverse impacts on the Antarctic environment and dependent associated ecosystems including significant changes in distribution abundance or productivity of species, jeopardy to endangered and threatened species, as well as degradation or risk to areas of biological significance [Protocol on Environmental Protection to the Antarctic Treaty (1991)]. Noise is not specifically listed, but its implicit inclusion will be discussed later in this chapter. The Arctic Environmental Protection Strategy (AEPS) is more direct in its discussion on the concerns of ocean noise on the Arctic environment. The AEPS deals with four major themes, the first of which is the monitoring and assessment of contaminants. The Arctic Monitoring and Assessment Programme (AMAP) was established under the AEPS and is designed to evaluate 6 major pollution issues identified in the strategy: persistent organic contaminants, oil, heavy metals, noise, radioactivity, and acidification. The 8 Arctic countries who signed the AEPS later formed the Arctic Council which is a forum for discussing social, economic, and environmental development in the Arctic. The Rovaniemi Declaration on the Protection of the Arctic Environment, signed in 1991 by the members of the Arctic Council, commits members to: "Cooperation in scientific research to specify sources… and effects of pollution, in particular…noise… as well as sharing of these data" and recognizes moving sources of noise as points of concern (Rovaniemi Declaration in Declaration on the Protection of the Arctic Environment 1991). However, it is the AEPS that is the mechanism providing for environmental protection in the Arctic. Once again, despite the recognition of the issue, no further steps have been taken to enforce these provisions.

Nation-State Provisions

Several countries have their own legal framework for the protection of wildlife and the environment. This discussion will focus on a sample of those countries which have comprehensive and sophisticated environmental and ecological protection legal regimes. The section provides a preliminary look at some of the available frameworks that could provide support for an international approach, but is by no means exhaustive.

Australia's Environment Protection and Biodiversity Conservation Act of 1999 (EPBC Act) provides for the identification and listing of key threatening processes. Processes that qualify would adversely affect two or more listed threatened species or threatened ecological communities. Currently, anthropogenic noise production or use is not listed as a threatening process, although potential framework through other government actions exists for future steps to minimize noise perturbations. For example, in 2003, proposed seismic testing in the Twelve Apostles Marine National Park was prohibited by the Environment Minister claiming that testing would have detrimental impacts on the coral breeding season. This type of prohibition provides a precedent for future actions to mitigate impacts of seismic noise on sensitive populations. If shown to be significant, the argument can be made for vessel traffic to constitute a significant perturbation to sensitive marine populations and provides for its regulation or prohibition in certain areas (No Seismic Tests at Twelve Apostles, October 17, 2003). Australia has also implemented a pilot program for vessel guidance through the Torres Strait that expands the boarders of its current Particularly Sensitive Sea Area (PSSA). Through this expansion, Australia can regulate activities of vessels within these waters, such as requiring pilot guided vessels (Beckman, R., 2007). They can also require speed reductions and change Traffic Separation Schemes (TSS) or shipping lanes for added protection to sensitive populations in the area. By creating this PSSA, Australia has given itself added ability to regulate the activities that occur within that area and require that transiting vessels comply with these regulations. Although not directly linked with their EPBC Act, the creation of the PSSA adds a regulatory component for vessel traffic or other pollution emitted in the environment not already covered.

The Canadian Oceans Act also expresses commitment to protecting the environment through "the wide application of the precautionary approach to the conservation, management and exploitation of marine resources in order to protect these resources and preserve the marine environment" (Beckman, 2007). Canada has other legal frameworks such as the Species at Risk Act, the Department of Fisheries and Oceans Act, and the Canada Shipping Act of 2001 which specifically lists "protect the marine environment from damage due to navigation and shipping activities" as one of its objectives (S.C. 2001, c. 26).

The U.K. wildlife laws are also designed to protect the marine environment. For example, the Countryside and Right of Way Act of 2000 specifically prohibits reckless disturbance of cetaceans. This act extends the protection already in place under the European Habitats Directive. Additionally, the Wildlife and Countryside Act 1981 provides protection for cetaceans specifically in U.K. waters. The U.K. is also a member state of the ASCOBANS agreement, and thus recognizes the same need for addressing the effect of noise on cetacean populations. The commitment to protection by the U.K. is expanded by and often complimentary to European environmental protection measures for comprehensive protection of joint waters. Europe has the Joint Nature Conservation Committee (JNCC) which is responsible for setting mitigation rules for active acoustic projects as well as other monitoring and mitigation work.

The United States has three important laws, the Endangered Species Act (ESA), the National Environmental Policy Act (NEPA), and the Marine Mammal Protection Act (MMPA). Each has pieces, that when combined, could become the framework for more comprehensive protection and abatement of underwater noise perturbations. The Endangered Species Act it prohibits the 'taking' of any animal listed as endangered which includes significantly modifying its habitat (16 U.S.C. § 1531 – 1534). Because the majority of marine mammals found in U.S. waters are considered endangered, and it is well established that noise perturbations have negative effects on the ocean environment (the habitat of the marine mammal), exposure to noise should be considered as a potential taking and need to be permitted as such.

NEPA requires an impact statement [Environmental impact statement (EIS) or Environmental Impact Assessment (EA); EA- briefly provides sufficient evidence and analysis for determining whether to prepare an EIS; it aids an agency's compliance with

NEPA when no EIS is necessary; and it facilitates preparation of an EIS when one is necessary. EIS is a detailed analysis that serves to insure that the policies and goals defined in NEPA are infused into the ongoing programs and actions of the federal agency. EISs are generally prepared for projects that the proposing agency views as having significant prospective environmental impacts] for federally funded or permitted activities that have a significant impact on the environment. This assessment and statement should provide a discussion of significant environmental impacts and reasonable alternatives (including a No Action alternative) which would avoid or minimize adverse impacts to the environment (42 U.S.C. § 4321 et seq.). Current scientific research shows that noise from shipping negatively impacts marine mammal populations, many species of which use areas around or adjacent to ports and shipping lanes. The potential exists for future requirements for projects using federal funding to address noise from ships and provide appropriate mitigation measures to minimize impacts.

Last, is the MMPA. This act defines two levels of harassment. Type A harassment is "any act of pursuit, torment, or annoyance which has the potential to injure" and type B harassment is any act of pursuit, torment, or annoyance which has the potential to disturb (breeding, migration, feeding, nursing, sheltering, breathing) a marine mammal (16 USC § 31). Ideally, clearer distinctions between harmful and safe practices need to be developed so that regulations and permits such as General Authorizations [1994 amendments to the MMPA procedure for obtaining permission to conduct research activities involving only Level B harassment on non-ESA listed marine mammals] have clearer definitions for more directed and wide reaching application.

One of the issues with the MMPA is that it specifically identifies activities that intentionally or knowingly interact with marine mammals (i.e., science, seismic, Naval operations) and does nothing for other interactions. In other words, regulated activities are those which adhere to the permitting process. Only through request and approval of a permit are the terms of the permit enforceable. For example, shipping companies, although arguably harassing marine mammals, do not need a permit to operate, and thus are not subject to the restrictions of operating under a permit.

There is unequal burden on different industries and activities which must apply for a permit creating unequal regulation. A different example is with fishers who may incidentally take a marine mammal. Their fishing practices do not require a permit other than for the fish they catch; (Yaggi, M., 1996) however, a scientific study using fish trawls would require a permit to take marine mammals. Additionally, the issue of controlled exposure experiments raises the same discrepancy. Scientists are required to have a permit to play back the sounds of passing vessels; however, the vessels do not require a permit under the MMPA to transit through the same area (McCarthy and Lichtman, 2007). Once again, it is generally accepted that noise from vessel traffic has the potential to harass marine mammals by disrupting their communication, feeding, and migration patterns which all fall under level B harassment and should be openly considered as a future permitted activity.

There exists a common thread throughout the plans discussed so far. The precautionary principle is mentioned consistently within recommendations for addressing anthropogenic impacts on the marine environment. Even in those documents that do not address noise specifically, the need to conserve and protect the environment through precautionary action is established. Richardson et al (1995) and multiple National Research Council (NRC), National Resource Defense Council (NRDC), OSPAR Commission reports and other international reports have all discussed the negative impact different noise sources have on marine mammals as well as other marine organisms such as fish and cephalopods. It is well established that seismic activities, naval operations, and noise from vessel traffic disrupt feeding, migration and communication patterns (Richardson et al., 1995; Jasny, 2005; National Research Council, 1994). The precautionary principle requires that errors be made on the side of environmental protection (Atapattu, 2002). Even with strong scientific evidence, little or no action has been taken to curb noise emissions from vessels or to even list this type of energy as pollution (see Chapter VI). However, even without specifically being addressed by some international agreements, noise has already been established as a source of stress and perturbation in the marine environment. Based on the overarching commitment to ecological protection and conservation combined with the commitment to act within the precautionary principle, confronting the issue of marine noise is implicitly required and action should be taken to reduce noise emissions. A recent (2009) document submitted to OSPAR by review committee states: "Our current knowledge on the impacts of underwater sound on marine life is incomplete, frequently inconclusive and occasionally contradictory. Nevertheless, it is clear that man-made underwater sound becomes a form of pollution when it harms or is likely to harm marine life… This overview document [OSPAR publication number 441/2009: Overview of the impacts of anthropogenic underwater sound in the marine environment] lays the scientific basis for OSPAR to design future management measures in order to tackle this emerging source of pollution and also complements concerns raised by ASCOBANS." This represents a major step towards future regulation of noise through the recognition of necessity for management upholding the commitment to the precautionary approach.

International Framework for Noise Pollution Management

Internationally, there are three major contributors to environmental protection that also possess the framework to address environmental regulation of noise pollution. The United Nations Convention on the Law of the Sea (UNCLOS) III specifically identifies energy as a type of pollution (UNCLOSE art. 1(1) (4), 21 I.L.M. 1261, 1271). Since sound is a type of energy, any unwanted or negative sound energy emitted into the oceans could be classified as pollution and therefore fall under the UNCLOS III definition of inputs into the marine environment that should be prevented. This is one of the most important distinctions between UNCLOS III and other international conventions that deal with controlling pollution in the marine environment.

The convention also requires accountability between nations. Article 194 explicitly states that: “States shall take all measures necessary to ensure that activities under their jurisdiction or control are so conducted as not to cause damage by pollution to other states.” (UNCLOS. Art. 194 (2)). Much of the language for article 194 is derived from the Trail Smelter Case in 1941 which found that in addition to reparations, States have a duty to take appropriate measures to protect the environment (Trail Smelter Arbitration, 1941). This duty is similar to the requirement in the precautionary principle to protect the environment unless the proponents of the activity can prove that their actions will not have unacceptable impacts. This duty of accountability is expanded in later articles in UNCLOS III not only to protect the environment but to monitor the actions of others who might.

Articles 204 and 206 require the surveillance of activities likely to pollute and to assess potential effects of any planned actions that might have a negative impact on the environment. Possible Future exploration of the language portends the potential for these articles to outline the idea of a global environmental impact assessment (not unlike United State’s NEPA) for actions concerning the ocean (UNCLOS Art. 204 and UNCLOS Art 206).

Unfortunately, like the other international conventions (excepting UNCLOS III subsequent migratory fisheries agreement) UNCLOS III lacks teeth for any enforcement measures where ocean noise pollution is concerned. Where UNCLOS lacks teeth, the

IMO and its promulgated Convention on Prevention of Pollution from Ships might provide the solution.

The International Maritime Organization (IMO) is a specialized organization created by the United Nations and charged with the responsibility for the safety and security of shipping and prevention of marine pollution by ships. Although the IMO does not specifically recognize noise as a source of pollution, their Particularly Sensitive Sea Area (PSSA) program does. IMO resolution A.927 (22), adopted in 2002 (for identifying PSSA), states that: "in the course of routine operations, ships may release a wide variety of substances… and even noise. As areas of heightened sensitivity, PSSAs would also have the ability to enact stricter regulations on emissions from ships. The recognition of noise as a possible emission from ships under PSSA designation means it may be possible to regulate vessel noise emissions within these areas. Thus far, the IMO has made no move to create such regulations and, in fact, "As regards operational pollution, there is a strong preference within IMO and its Member States for the development of globally uniform regulations rather than a proliferation of diverse regional or local standards", as would be the case with a network of PSSAs (A.720 (17) 1.4.3). This idea of global standards is reiterated in later resolutions for PSSAs describing the rationale based on "A Special Area may encompass the maritime zones of several States, or even an entire enclosed or semi-enclosed area. Special Area designation should be made on the basis of the criteria and characteristics listed in paragraphs 2.3 to 2.6 to avoid the proliferation of such areas" (A.927 (22) 2.2).

The International Convention for the Prevention of Pollution from Ships (MARPOL, 1973, amended 1978) promulgated by the IMO's Marine Environmental Committee does not discuss noise pollution. However, it has multiple annexes which address many different kinds of marine pollution. These annexes form the framework for ship design and construction requirements as well as emissions standards. These standards could be applied towards managing noise pollution either through re-interpretation of the definition of a harmful substance or through an addition of a new annex. Currently, Article 2.2 of MARPOL defines a harmful substance as "any substance which, if introduced into the sea, is liable to create hazards to human health, to harm living resources and marine life, to damage amenities or to interfere with other legitimate uses of the sea, and includes any substance subject to control by the present Convention." If and when vessel noise is specifically identified as a harmful substance, it would be included in the definition and thus able to be regulated under MARPOL. Because noise is a form of energy and not a physical substance, it may be more feasible to create a new annex specifically addressing energy emissions into the marine environment. Either option would allow new regulations to be promulgated under MARPOL for the prevention of noise pollution by ships

Proposed Guidelines for Marine Noise Emissions

Although a global framework is needed, it should to be based on conclusions from applied research, some of which is presented through regional focus groups and conventions. These findings may provide valuable starting points for noise abatement strategies where a praxis of solid scientific findings can be applied.

In April of 2010, the Joint Research Center (JNC) (European Union's scientific and technical research laboratory) and the European Commission published their Marine Strategy Framework Directive Task Group 11 Report on Underwater noise and other forms of energy. In this directive, they attempt to outline guidelines for sound emission into the environment. The Table 11 shows their delineation for low, mid, and high frequency noise emissions and their recommended standards (Tasker et al., 2010).

Table 11: Breakdown of the criteria to assess impacts on marine mammals and suggestions for limits on noise emissions.

TG11 Energy		
ATTRIBUTE	**Criteria** to assess the descriptor	**Indicators** to be measured
Underwater noise - Low and mid-frequency impulsive sound	High amplitude impulsive anthropogenic sound within a frequency band between 10Hz and 10 kHz, assessed using either sound energy over time (Sound Exposure Level SEL) or peak sound level of the sound source. Sound thresholds set following review of received levels likely to cause effects on dolphins; these levels unlikely to be appropriate for all marine biota. The indicator addresses time and spatial extent of these sounds.	The proportion of days within a calendar year, over areas of 15'N x 15'E/W in which anthropogenic sound sources exceed either of two levels, 183 dB re 1μPa^2.s (i.e. measured as Sound Exposure Level, SEL) or 224 dB re 1μPa$_{peak}$ (i.e. measured as peak sound pressure level) when extrapolated to one metre, measured over the frequency band 10 Hz to 10 kHz
Underwater noise – High frequency impulsive sounds	Sounds from sonar sources below 200 KHz that potentially have adverse effects, mostly on marine mammals, appears to be increasing. This indicator would enable trends to be followed.	The total number of vessels that are equipped with sonar systems generating sonar pulses below 200 kHz should decrease by at least *x*% per year starting in [2012].
Underwater noise – low frequency continuous sound	Background noise without distinguishable sources can lead to masking of biological relevant signals, alter communication signals of marine animals, and through chronic exposure, may permanently impair important biological functions. Anthropogenic input to this background noise has been increasing. This indicator requires a set of sound observatories and would enable trends in anthropogenic background noise to be followed.	The ambient noise level measured by a statistical representative sets of observation stations in Regional Seas where noise within the 1/3 octave bands 63 and 125 Hz (centre frequency) should not exceed the baseline values of year [2012] or 100 dB (re 1μPa rms; average noise level in these octave bands over a year).

These standards are a good starting point for future elaboration. The difficult and unfortunate part about setting standards is that they need to be far reaching in their applicability for researchers and industry on a global scale. Using the units in the above rubric as an example, there are several different ways to measure noise and the rubric has most of them, none of which are directly comparable. If, for example, the species of interest is sperm whales, they are exposed to all three kinds of noise which all potentially overlap with their broad band clicks. The low to mid frequency range for impulsive signals is applicable when considering noise impacts for those mammals with mid – frequency range like most odontocetes, but the measurement is for impulse sounds only. Because sperm whales, as with most cetaceans, are found around the globe in both coastal and thalassic waters, standards, like the Sound Exposure Level (SEL) calculated for the low frequency noise, also needs to be calculated for mid frequency: near field ship passages are broadband signals extending into the 5kHz range. Conversely, impulse sounds like airguns can be very low frequency and while they are impulse sounds, a typical seismic survey shoots every 15 seconds. That is certainly more than just a single exposure and should definitely be considered in SEL calculations for all regions. In other words, noise regulations need to account for all foreseeable possibilities. The calculations should not be complicated: they should be repeated measures made using the same units (where possible) to avoid confusion and make comparisons of noise measurements by both the scientific and industrial community simple and easy to understand. The JNC rubric is a solid starting point. Coupled with the science prescribed by the regional frameworks, the JNC provides the foundation upon which language should be easily expanded.

Vessel Noise Genesis and Potential Quieting Technology

One initial step for developing noise emission standards is to understand the current technology available for ship quieting efforts. The Final Report of the 2004 NOAA Symposium, “Shipping Noise and Marine Mammals,” discussed sources of vessel noise as well as some recommended ship quieting technology.

For any vessel, sound is generated through direct paths such as propeller motion, onboard machinery and turbulence around external ship elements. Indirect or “flanking” paths (e.g. sound from engine mounts through cables and ducts) ultimately transmit noise through the hull of this ship and can be as loud as direct transmission such as from the engine block to the hull. These types of machinery noise tend to dominate at low ship speeds; however, as vessel speed increases, flow (of water along the hull) and propeller noise predominate.

To combat acoustic radiation from vessels there are a number of sound-isolating and absorbing technologies available. Modern diesel electric engines may be fitted with resilient isolation mounts (in some cases double mounts), flexible hoses, and pipe hangers to minimize radiated sound. Acoustic filters, desurgers, and flow control valves may also be used to minimize sound emanating from fluids flowing to and from engine equipment. The use of electric drive propulsion can also be effective when economically feasible and results in lower machinery radiated noise. Flow noise around the hull is generally minimal compared to that generated by propeller cavitation and machinery noise, but is increasingly important at increased speeds. There are a number of mitigation methods including damping and decoupling, but flow noise is most effectively dealt with at the design stage and more difficult to address through retrofit.

The majority of radiated sound from large vessels is the result of propeller cavitation. Therefore, not surprisingly, much of the effort in quieting vessels focuses on propeller design and operation that limit or reduce cavitation. According to the report, several methods of propeller cavitation noise reduction are not only economically feasible, but may also lower fuel costs in the long run, saving money. In addition, the committee found that more frequent maintenance on props and hulls could significantly reduce noise emissions. While this would mean up front maintenance costs for shipping companies, this type of proactive equipment maintenance extends the life of the vessel and thus protects and increases the yield from the initial investment. The report recommends a complete cost/benefit analysis comparing the different technologies for the application of all types of noise reduction technology in an effort to find the most cost-effective and noise efficient combination (Southall, 2004). In order to develop standards and the voluntary adherence to them, a concerted effort to maintain a dialogue focused on science, technology, and economic viability of quieting processes among stakeholders about the impacts of noise perturbations is imperative.

One avenue that may promote education as well as continual improvement of industry practices is ISO 14001. This is where companies who want to be ISO 14001 certified would have the potential to attain a higher marketability through a better reputation with the international community (von Zharen, 1996). ISO 14001 certification is earned through demonstrated commitment by companies to environmental awareness and continual improvement within their business practices by creating a business plan that ensures compliance with all applicable legal requirements. The ISO 14001 standard goes a step further: it requires improvement of environmental management strategies for reducing negative impacts on the environment.

Development of such a plan for a shipping company might include objectives like upgrading to fuel efficient engines or cleaner burning fuels to reduce air pollution. Likewise, measures to reduce noise emissions could also be part of the plan, and the adherence to these goals with measureable progress made over time would demonstrate to customers and investors that their company is committed to protection of the marine environment. In an age where green energy and recycling materials are becoming ideal alternatives, environmental certification may offer a business edge and make these environmentally friendly changes also business friendly.

Support for Changes to Traffic Separation Scheme, Shipping Lane Organization, and Speed Reduction Recommendations on the Louisiana- Mississippi Shelf

Alternate management possibilities include using already established framework for ship strike reduction in great whales. One of the most immediate contributors to large marine mammal mortality is ship strikes. Evidence for this exists from studies of blue, humpback, right, and fin whales along the east and west coasts of the U.S. One of the ways to combat this human induced mortality is through changes in ship speed regulations and the rerouting of major shipping lanes. For example, case studies for the Nova Scotia ship lanes in Rosen Bay as well as the changes in traffic separation scheme for the approach into the Boston Harbor have shown reductions in ship strikes with great whales.

The IMO currently requires Automatic Identification System (AIS) transponders on all international vessels ≥300 gross tonnage and on all passenger vessels (Vanderlaan and Taggart 2009). AIS transponders provide information about a vessel's static information such as name, dimensions, and IMO number. They also transmit real time information such as position, speed, direction, destination, Estimated Time of Arrival, and draft. This information is transmitted via VHF signal to any number of shore based receivers and is in standard National Marine Electronics Association (NEMA) format.

In 2007, changes were made to the Traffic Separation Scheme (TSS) for the approach around Cape Cod, MA (Great South Channel). The rationale behind these changes was to reduce the incidence of ship strike of North Atlantic right whales, an endangered population. In response, the lanes were narrowed by one half mile in both directions, moving the shipping lanes out of the areas of highest right whale seasonal densities (Abramson et al., 2009).. In addition, recommendations were made for seasonal areas of ship speed reduction for ships over 300 gross tones from April 1- July 31.

These changes were made based on the joint proposal from the Office of National Marine Sanctuaries, NOAA Fisheries Office of Protected Resources, and NOAA's General Counsel for International Law to the International Maritime Organization. It took approximately 7 years for the IMO to adopt this measure, partly due to the data requirements from the IMO and the multiple groups involved. Traveling within these lanes is not required by USCG or IMO but failure to follow TSS often carries liability should a collision or other incident occur [Liability or fault would be determined based on the International Regulations for Preventing Collision at Sea (COLREGs) of 1972 which have also been adopted by the US Coast Guards. Rule 10 of the Collision Regulations deals with the conduct of vessels in or near traffic separation schemes adopted by the Organization. By regulation 8 of Chapter V (Safety of Navigation) of the International Convention for the Safety of Life at Sea, 1974 (SOLAS), IMO is recognized as being the only organization competent to deal with international measures concerning the routing of ships. Vessel failing to comply with these regulations can be declared in fault by the respective court, and therefore, liable for the collision]

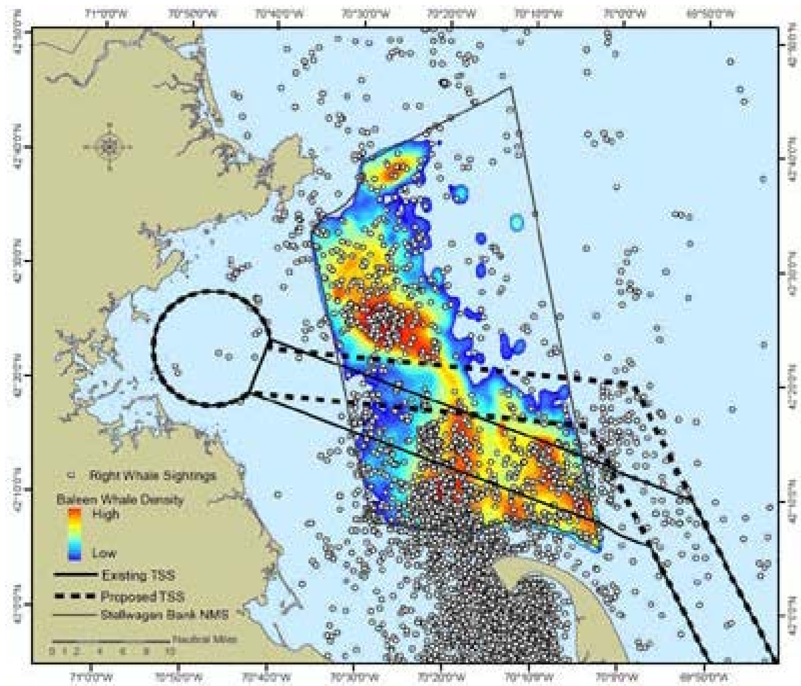


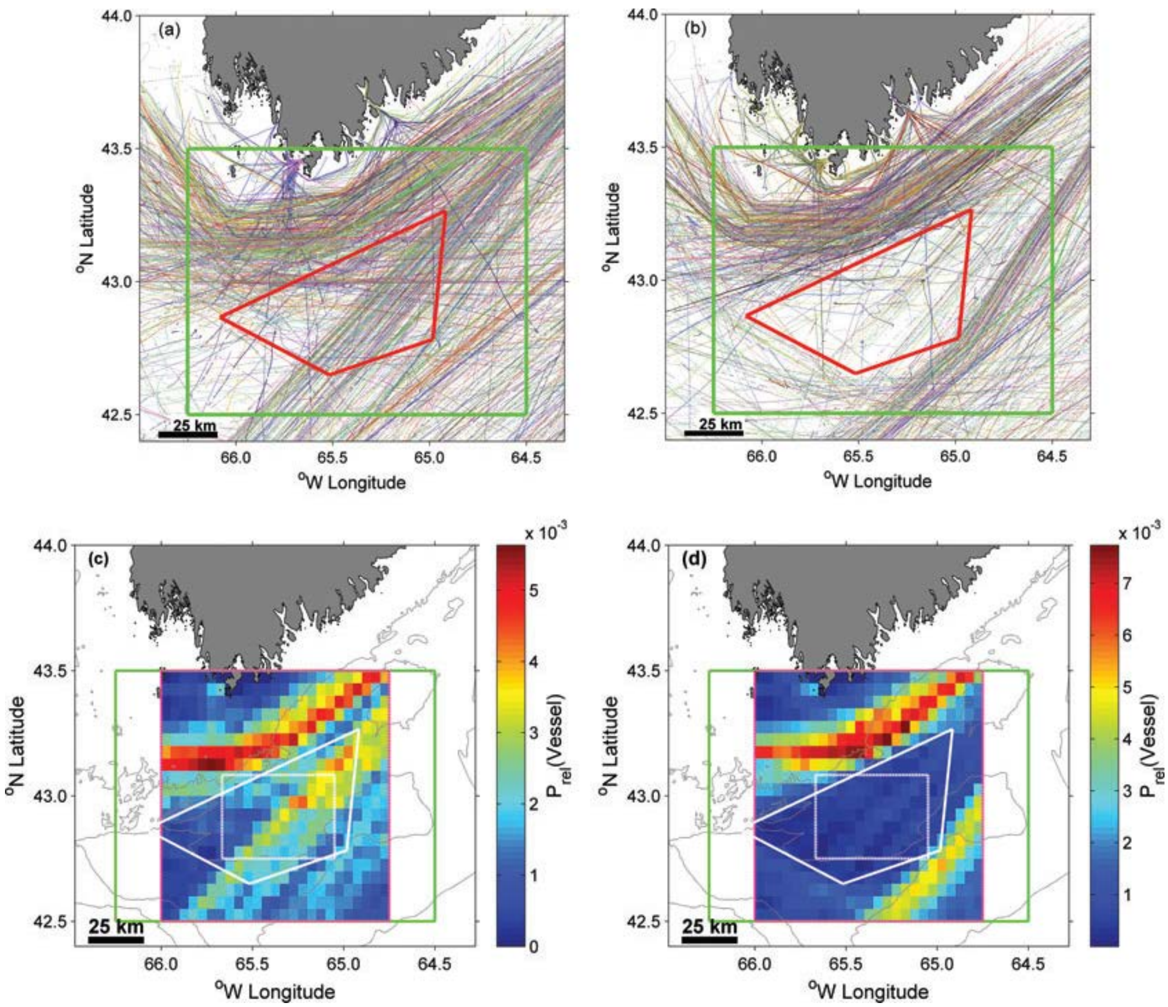
Figure 34: Map of Right Whale Distribution and Traffic Separation Scheme in Cape Cod Bay and the Great South Channel. Shift in the Traffic Separation Scheme, shown by dotted lines, to avoid high density areas of baleen whales (Abramson et al., 2009).

In the above figure [Figure 34)], the solid lines represent the old TSS which completely passes through areas of high whale density. The dashed line represents the new TSS which appears to bisect two areas of high whale density.

Since their implementation in January 2009, preliminary AIS monitoring by both the National Marine Fisheries Service (NMFS) and Stellwagen Bank National Marine Sanctuary (SBNMS) indicate that only about 50% of vessels have been complying with the speed reductions below 10 knots in Sensitive Marine Areas (SMA) (Abramson et al., 2009). A more recent study using AIS data differentiated between compliance and commitment with compliance being a binary yes/no [established based on analysis of vessel speed data from AIS data] for obeying the speed reduction and commitment being the percent of distance traveled that exceeded the 10 knot requirement. The calculated commitment shows the percent of time a ship transiting through the area is not in compliance. This is a better indication of overall adherence to regulations since any vessel not following the speed restriction would be considered non-compliant even if it were only for a short time. Using commitment is a more realistic way to evaluate the degree of compliance over the entire area. The study showed that when speed restrictions were in effect, vessels normally exceeding 10 knots slowed down, decreasing the time they were normally not in compliance (68% [cargo]- 58% [tankers]) by greater than 9 percentage points (Thompson et al., 2011). Data on compliance with TSS were not available.

Similar recommendations were put into effect in Nova Scotia for the Roseway Basin Area (Vanderlaan and Taggart, 2009) on the Scotian Shelf. This area was recognized by the IMO as a voluntary conservation initiative to reduce the number of right whale ship strikes in the area. The International Maritime Organization's (IMO) Sub-Committee on the Safety of Navigation approved the proposal from Transport Canada that the Roseway Basin area to be declared an "Area to be Avoided" (ATBA) by shipping. This area to be avoided (ATBA) was implemented in Canada on May 1, 2008, and is seasonally in effect from June 1st -December 31st. Estimates of vessel operator compliance within the first 5 months ranged from 57%-87% with an average of 71% +/- 11%. While compliance with the ATBA was not complete, those vessels that did transit the area did so at a significantly lower average speed (28.1 km/hr compared with 31.2 km/hr) during the time of the seasonal speed restriction (Vanderlaan and Taggart, 2009). Figure 35) shows the success of the recommended ATBA. The two maps on the left (a, c) are AIS data ship tracks from prior to when the restrictions went into place and maps on the right (b, d) are from post restrictions. The top two maps (a, b) show the overlay of individual ship tracks while the lower maps (c, d) show number of ships cumulatively. There is a clear difference from before and after figures: while not all ships avoid the area, the difference is visibly significant, and those ships that transited through did so at lower speeds. Although not a perfect strategy, these recommendations are clearly capable of making a difference and vessel operators have shown willingness to comply with these new measures.

a) b)



c) d)

Figure 35: (a, b, c, and d) The area to be avoided (ATBA) before and after recommended avoidance measures were established for Rosen Bay, Nova Scotia. It is possible to see where the ships have deviated from their previous tracks in deference to the recommended area.

The final example demonstrating the efficacy of these TSS and speed restrictions is in the right whale calving grounds off the coast of Georgia and Florida. Interestingly, similar results were found with compliance based on speed or route recommendations. By publishing suggested shipping routes in an out of three ports, Brunswick, Fernandina Beach, and Naval Station Mayport, the traffic was greatly constrained, resulting in larger areas without ships and more defined lanes for ships moving along the coast. Initially, the reduced speed measures were only recommendations that ships would follow on a voluntary basis. Although only 16% of vessels complied with the voluntary speed reductions, recommended new routes were followed 75% of the time. Mandatory restrictions were passed by NOAA in 2008, requiring speeds below 10 knots. Average vessel speed concurrently reduced to 10.5 knots, which demonstrates an incomplete compliance with the regulations, but an overall decrease in vessel speed through the area. As with the other areas with speed restrictions, results of the study showed that required speed restrictions were successful and can be an effective way to reduce ship speed through areas identified as ecologically sensitive. Additionally, compliance with the recommended routes increased over time from 43% prior to any speed recommendations, to 52% during the first year and finally 96% in the final year of the study (Lagueux et al., 2011). Figure 36), below shows the seasonal management area boundaries as well as the recommended shipping lanes out of the four major ports along the Georgia-Florida coast.

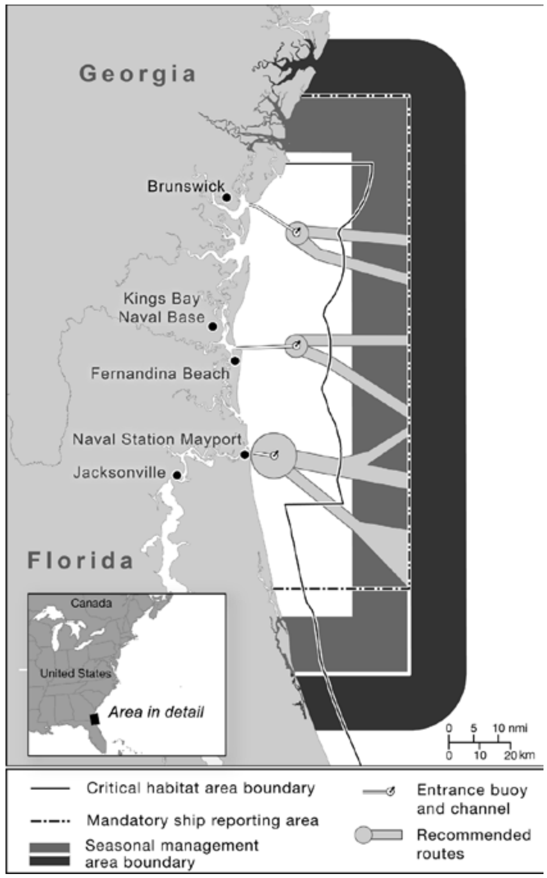


Figure 36: Map of Right Whale Calving Grounds Management Area off Georgia and Florida, U.S.A. Seasonal management boundary areas and ports off Georgia and Florida, U.S.A. (Lagueux et al., 2011).

Figure 37) demonstrates the progression of recommended shipping route compliance over the 4 years of the study. There is a clear progression towards compliance even though the recommendations are only voluntary.

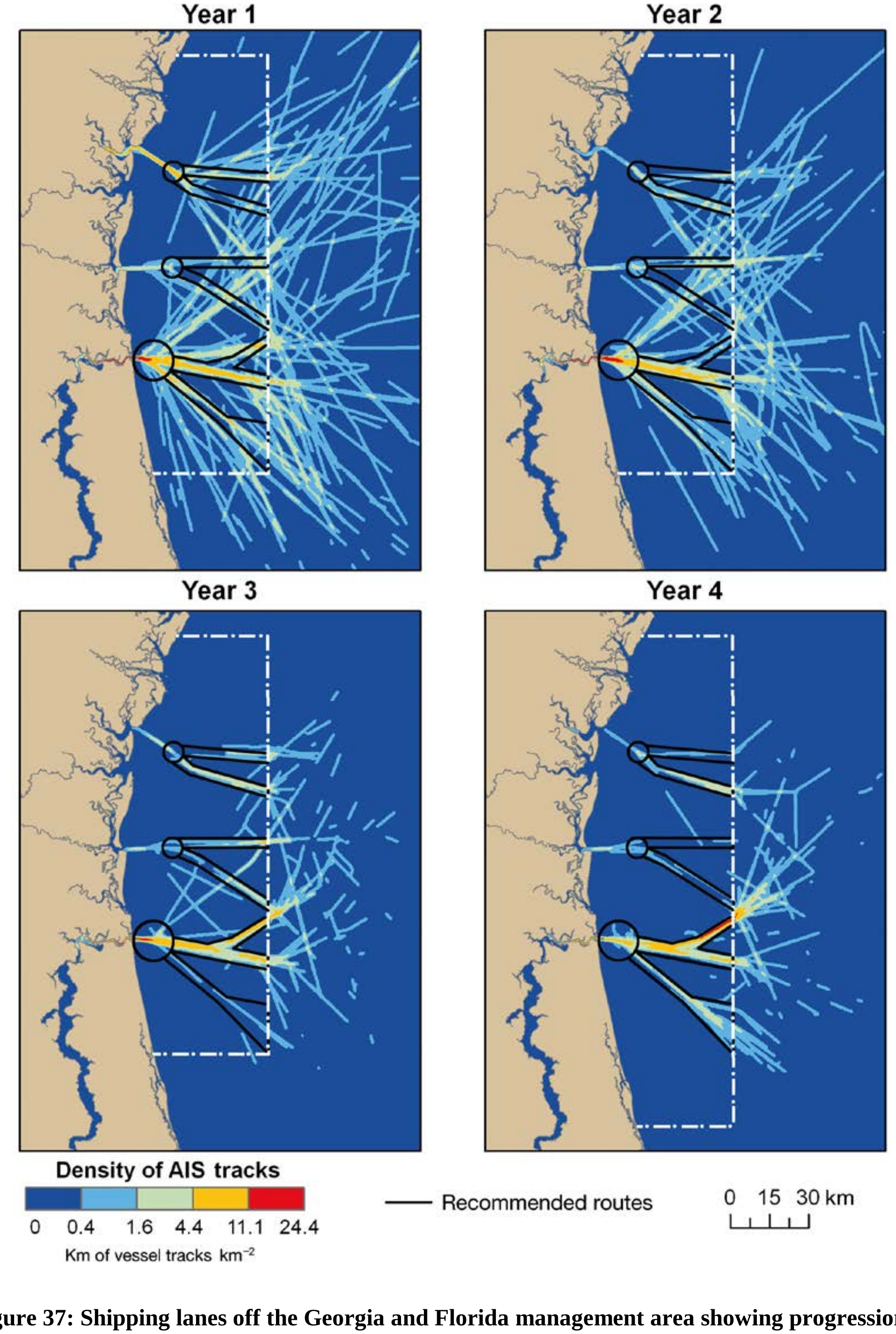


Figure 37: Shipping lanes off the Georgia and Florida management area showing progression of compliance with voluntary shipping lanes over the four year study.

Although only recommendations and voluntary measures, these types of management strategies could be very useful for managing ship traffic in the GoM. Given the overlap of ship traffic with areas of high concentrations of sperm whales, reducing vessel speed and limiting the traffic patterns could also reduce areas of noise exposure and limit behavioral impacts due to perturbations from vessel noise. These strategies could be managed by U.S. Coast Guard and, particularly with vessel traffic routes, could have significant success through completely voluntary measures if similar strategies are any indication. While this will not address the global issue, for regional management in areas of high traffic, it is a strong first step.

CHAPTER VIII

SCIENTIFIC MANAGEMENT RECOMMENDATIONS FOR THE GULF OF MEXICO

The GoM is a center of marine activities, from seismic exploration to shipping, drilling, platform installation, lightering, and construction, among others. In 2008, more than 14,000 ships passed through the Port of New Orleans and Port of Houston combined (approximately 6,000 vessel calls were recorded at the Port of New Orleans and 8,000 vessel calls at the Port of Houston [Port Authority of Houston, 2009; Port Authority of New Orleans, 2009]). The GoM shipping lanes play host to both international and interstate commerce. Both Houston and New Orleans are in the top ten ports for cargo worldwide and in 2009, New Orleans handled over 27 million tons of bulk, cargo and container materials. The noise from these vessels is continuous and may be a significant source of stress for animals in the marine environment. This is of particular concern for the resident sperm whale population in the GoM because they are most abundant on the Louisiana-Mississippi shelf and in the direct path of a number of converging shipping lanes. They are also an endangered species. The strategy for reducing this impact – vessel traffic separation schemes and reduction of vessel speed as, described in the previous chapter - is a strong strategy for an immediate and enforceable way to address reducing perturbations from vessel noise on sperm whales and the other 29 species of marine mammal found in the GoM (Würsig et al., 2000).

Current Applicable Protection

Sperm whales are federally protected by both the Endangered Species Act (ESA) and the Marine Mammal Protection Act (MMPA). Under these laws, it is illegal to harm marine mammals in U.S. waters. Harm is defined by the ESA to include any action that causes behavioral changes of marine mammals or any type of harassment such as close approach by vessels (50 C.F.R. § 222 *et seq.*). The ESA prohibits the 'taking' of any animal listed as endangered which includes significantly modifying its habitat (16 U.S.C. § 1531 - 1534.). The Marine Mammal Protection Act (MMPA) defines two levels of harassment. Type A harassment is "any act of pursuit, torment, or annoyance which has the potential to injure" and type B harassment is any act of pursuit, torment, or annoyance which has the potential to disturb (breeding, migration, feeding, nursing, sheltering, breathing) a marine mammal (16 USC § 31). Until recently, anthropogenic noise had not been considered a major factor for behavioral changes. It is now recognized to be dangerous and sometimes fatal for marine mammals in close proximity to noise sources (Jasny et al., 2005). Thus, new attention must be given to the effects of chronic noise exposure, especially in an area as heavily trafficked as the GoM as well as all port areas with a marine mammal presence.

Proposed Action for Management

Sperm whales, because of their endangered status under the ESA, are considered a managed population, and therefore require a management plan. Unlike other cetaceans which compete directly with fisheries for their food source, sperm whales consume squid and other fish species but are not in direct competition with any commercial fishery. Therefore, while concerns of food web depletion are valid, their direct applicability to sperm whales is difficult to include in a management plan. Additionally, human interactions with sperm whales are uncommon. They are no longer hunted and their interactions with fishing gear, while probable, are not readily recorded. The biggest issue for sperm whales is their overlap with shipping vessels in their primary habitat. As such, the management strategy best suited is management of the shipping industry and vessel contribution of near field noise into the marine environment.

The following paragraphs examine potential available management strategies from a very simplistic staring point as a basis for establishing a dialogue on these important issues. There are several ways to address this management issue. It is possible to designate areas of environmental significance under the Marine Sanctuaries Act (NMSA). The Secretary of Commerce can designate and protect areas of the marine environment with special national significance due to their conservation… ecological… scientific, or esthetic qualities as national marine sanctuaries (16 U.S.C. § 1431 *et seq.*). These areas are managed by the NOAA National Sanctuaries office and require funding from NOAA to support the sanctuary making new sanctuaries, particularly large ones, difficult to create and maintain; however, designation as a Particularly Sensitive Sea Area (PSSA) is possible under IMO and would create a strategy to minimize impact of vessel traffic on sperm whales. It would also provide structure for working in cooperation with Bureau of Ocean Energy Management, (BOEM) (formally the Minerals Management Service, a federal agency under the Department of the Interior), which would be necessary for regulating seismic impacts. Based on the distribution of shipping in the GoM, the majority of vessels enter through the Florida Straits and heads towards Houston or New Orleans. The Florida Keys were designated a PSSA in 2002. Because of their proximity to the shipping lanes, it may be easier to extend that area and require ship quieting as a result. If that were possible, requiring ships to slow down to reduce vessel cavitation, water flow, and hull vibrations, while coming into New Orleans may be feasible. If the area along the Mississippi- Louisiana Shelf were designated as a PSSA, there is authority to make adjustments to shipping lanes, possibly controlling vessel noise through streamlining the lanes in the area (MARPOL 73/78 IMO res A.927 (22)). If possible, creating one major throughway from New Orleans over the Louisiana-Mississippi shelf that diverges further off the shelf could reduce noise by minimizing vessels in the primary habitat for sperm whales.

Title II of the Ports and Waterways Safety Act of 1972 (PWSA) states that “only the federal government may regulate the design, construction, alteration, repair, maintenance, operation, equipping, personnel qualification, and manning of tankers (33 U.S.C. §§ 1221-1236).” But it also allows for the Secretary of Transportation (U.S. Department of Transportation) to “prescribe different regulations applicable to vessels engaged in the domestic trade, and also may prescribe regulations that exceed standards set internationally. Regulations prescribed by the Secretary under this subsection are in addition to regulations prescribed under other laws… and include requirements for… **propulsion machinery** (author's bold)…" such as engines and propellers [(therefore, they can go beyond those set by MARPOL) (46 U.S.C. § 3703)]. Based on this portion of Title 46, the federal government potentially has the ability to require vessel quieting technologies on board all U.S. flag vessels.

In addition to the PWSA, the U.S. ratified certain MARPOL annexes and additionally passed the Act to Prevent Pollution from Ships (APPS) in 1980 the implementation legislation for MARPOL which requires all vessels within the U.S. territorial waters to comply with Annexes I, II, and V of the MARPOL Protocol [The navigable waters of the United States are: 1) the territorial seas of the United States; 2) internal waters of the United States that are subject to tidal influence; and, 3) internal waters of the United States not subject to tidal influence that are or have been used as highways for substantial interstate or foreign commerce. *See* 33 C.F.R. §2.36(a). [Territorial seas of the United States are the waters, 12 nautical miles wide, adjacent to the coast of the United States and seaward of the territorial sea baseline. In its present form, APPS essentially requires that all U.S. flagged ships, and foreign flagged vessels while in United States territorial waters, must comply with Annexes I, II, and V of the MARPOL Protocol (33 C.F.R. §2.22).]. Out of the top ten sea ports in the United States, seven are located on the GoM (U.S. EPA, 2011). So, if a ship is traveling through the Straits of Florida, or any portion of the GoM in U.S. waters, their destination is most likely a U.S. port; thus, at some point during their voyage, these vessels will be within the navigable waters of the United States. The APPS also authorizes the Secretary of Homeland Security to promulgate further regulations consistent with MARPOL. While MARPOL and its Annexes do not specifically address noise pollution, the IMO does through its PSSA framework. Instead of attempting to create a seventh annex to MARPOL addressing noise or energy as a pollutant, it may be possible to amend the U.S. APPS to include a clause for noise pollution from vessels within U.S. navigable waters. If Congress were to amend the APPS to include regulation for noise pollution from tankers, the U.S. Coast Guard would then be able to create a checklist for ships in U.S. ports to provide proof of compliance with maximum noise emission in navigable waters. This, by extension, would include the GoM (based on previous paragraph's discussion). Again, these examples provide only the basis for further examination and suggest hypothetical starting points for more complete analysis of regional and international laws and agreements.

This type of potential regulatory ability by Congress has already been demonstrated through the Oil Pollution Act of 1990. This act was passed in specific response to the *Exxon Valdez* oil spill. It requires that all tankers greater than 5,000 gross tons be equipped with a double hull (by 2010). This act applies not only to U.S. flag vessels but to all vessels entering U.S. waters (OPA 90 § 4115). As a result, changes to international regulatory regimes occurred via additions to MARPOL specifying configuration requirements for new tankers (73/78, Reg I/13F). Within U.S. waters, the U.S. Coast Guard is responsible for enforcement of this law. Although MARPOL does not recognize noise as a pollutant, the PWSA specifically addressed propulsion and engine noise which would include the equipment on ships responsible for the majority of the noise perturbations. Congress set a precedent for taking action on behalf of the environment to regulate ocean going vessels. It has within its power, as outlined in PWSA, the ability to also regulate ship design. While this may not solve the issue on an international level, by passing legislation in the U.S. (as with OPA 90), it may be possible to force the issue onto the international stage and address it more completely through an additional annex to MARPOL regulating noise from shipping. This is but another example of a possible legal channel through which vessel noise can be addressed through regulation of ocean going vessels. More thorough legal analyses are needed to identify all possible avenues applicable to this issue; however, those analyses are outside the scope of this dissertation.

A more immediate way to address this issue would be to create a set of voluntary, recommended shipping lanes as was done in the case of the protection plan for the North Atlantic right whale. The advantage of this approach is that the measures could be completely or partially voluntary depending on location. Additionally, mandatory measures could also come into effect such as those along the Georgia-Florida coast. Considering, however, that voluntary measures only require a request by NOAA or other agency to the public to solicit compliance, these measures may present an optimal first step toward regional management. To implement this type of approach, three pieces of information are key. The first is a comprehensive sightings database for sperm whales and all cetaceans in the GoM, particularly around the approaches to the Port of New Orleans. These data would then need to be mapped along with the AIS ship track data complied over multiple seasons to show distribution of usage. Lastly, current recommended Traffic Separation Scheme (TSS) patterns would need to be super-imposed to assess whether alterations in these patterns might benefit the current common lane usage as well as re-route around areas of higher aggregations of sperm whales. Figure 38) is an overlay of AIS ship position with a map of the GoM coast and its shipping lanes. The AIS data are for each ship position point received between January 12, 2011 and April 16, 2011. These are not individual ship tracks overlain, but rather the individual points. The map was broken into 100m squares and the number of points within each square summed for a density comparison. Areas where multiple ships were stationary over time appear as brighter circles unconnected to any obvious shipping lanes. The black dashed lines represent the official location of shipping lanes according to nautical charts provided by NOAA’s office of Coast Survey.

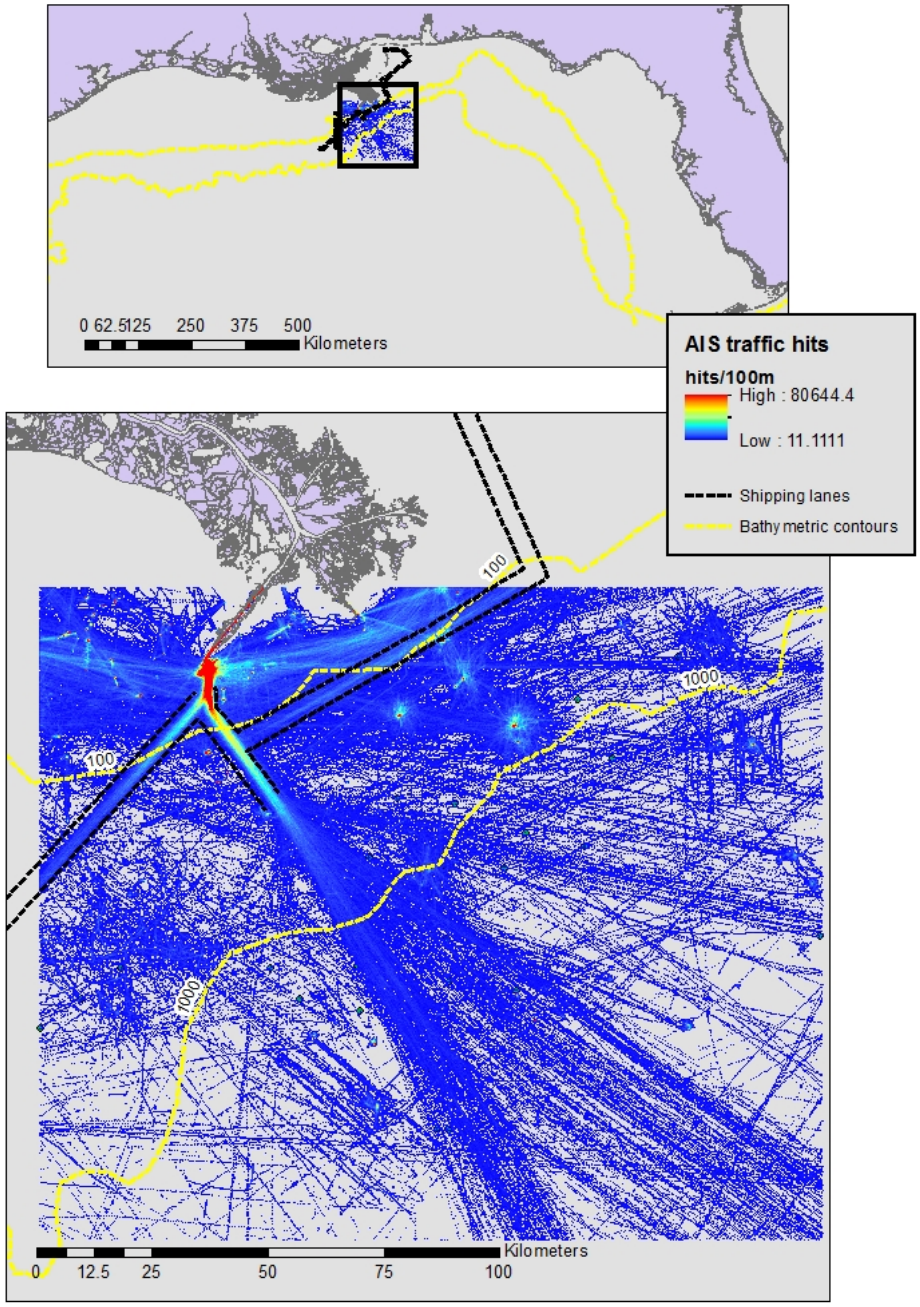


Figure 38: AIS ship positions on the approach to New Orleans. Areas with warmer colors (yellows/reds) indicate areas of higher ship densities; areas with cooler colors show lower densities (areas with densities below 0.0016 were dropped and are shown in white) (AIS data provided by Kyle Ward a Physical Scientist at NOAA's Office of Coast Survey. Map created by Brendan Hurley, GIS specialist).

Figure 39) below, shows an overlay of sperm whale locations taken from the 2010 annual stock assessment combined with the AIS position data in Figure 38) to display any potential overlap between areas of use. Additionally, current shipping lanes have been included to show overlap with both traffic and whales. Sperm whale positions were also analyzed for density distribution based on 20km grid sections. The areas with warmer colors (reds) show areas along the Louisiana shelf with higher densities of sperm whales. Not only is there conflicting use between whales and ships, overlapping ships transects one of the largest concentrations of sperm whale sightings in the GoM. This type of spatial representation is an important first step in any management approach for sperm whales in the GoM.

Visualizing these conflicts in resource use through maps is a valuable tool for understanding where changes in TSS and speed restrictions might have the largest positive effect on the whales sharing the environment. But it is not enough. Based on the information presented in this section, there are many options for managing the GoM through application of both federal and international legal regimes. Some of these measures are more difficult to implement such as large scale changes to international requirements for ship design. However, options like seasonal areas to be avoided, marine protected areas, or even particularly sensitive sea areas can all be applied on a small scale with varying amounts of federal or international approval.

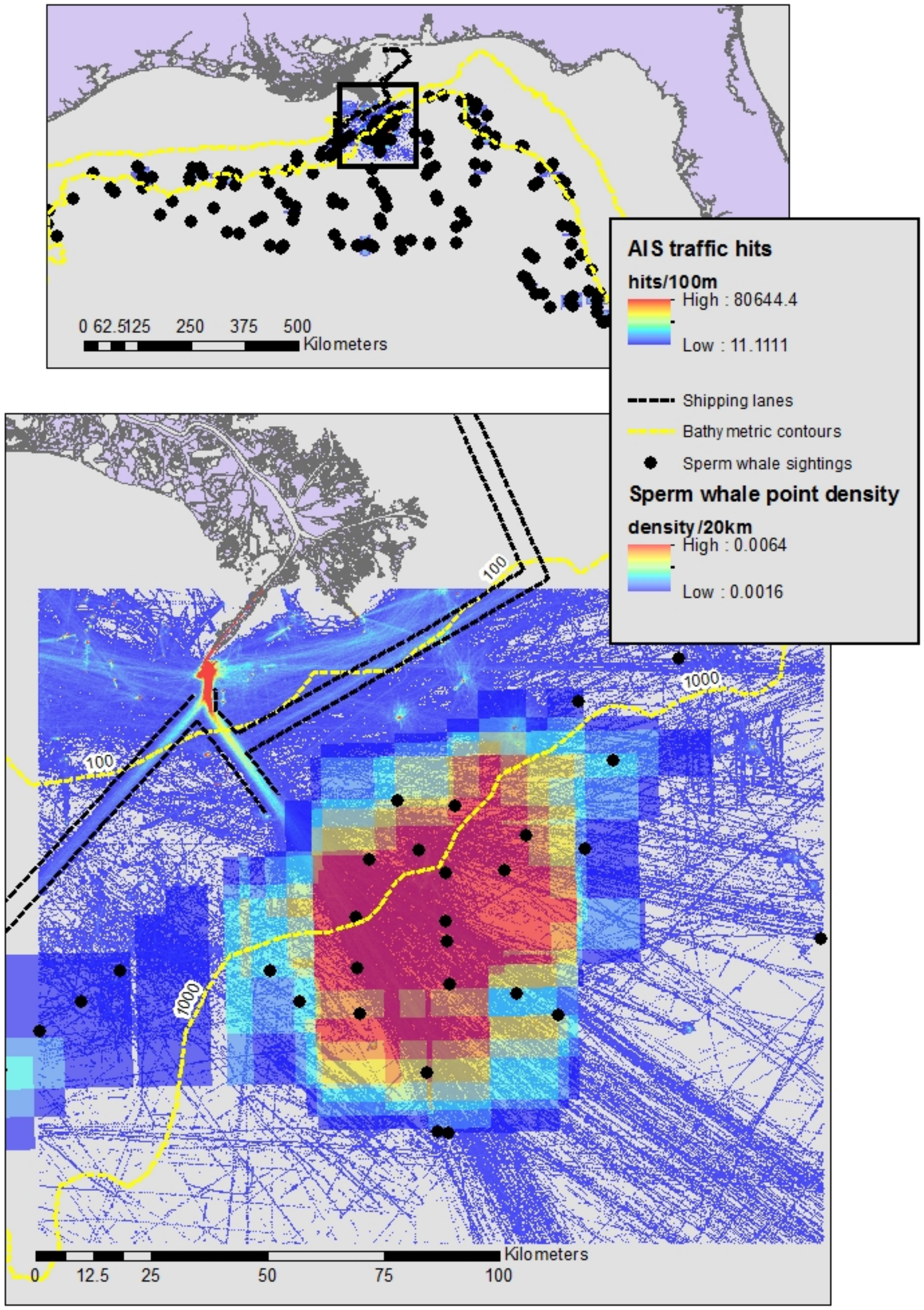


Figure 39: Map Showing Overlap of Sperm Whale Habitat with AIS Ship Positions and Shipping Lanes. Overlay of sperm whale locations taken from the 2010 annual stock assessment combined with the AIS positions to display overlap between areas of use. Areas in red are high density areas for sperm whales on the Louisiana- Mississippi Shelf, GoM.

In addition, changes to existing regulations such as the MMPA which would focus more on an ecosystem approach to permitting by requiring some accountability on the part of vessels captains could work to raise awareness and open dialogues to facilitate voluntary actions to reduce noise.

Conclusions

The type of framework, developed on the foundation of existing federal and international laws, is the strongest approach to creating future regulations for the protection of marine animals and the marine environment from perturbations from vessel noise. Concurrent with these types of measures, further research is needed to continue to understand the impacts of vessel noise on marine mammal communication. One of the most important purposes of these further research efforts will be to understand source level and how it translates into received level and ultimately into behavioral changes. Science and industry need to work together to develop standards for measuring noise as well as determining a standard unit for measure which can be compared across all noise types such as shipping, seismic, and naval. Pursuant to those standards, access to information on quieting technologies available to industry is necessary for drafting any proposed equipment regulations as is open dialogue with stakeholders to establish feasibility and timeframes for implementation. Ocean noise is not an issue that is going to go away. It needs to be addressed by means of research and management on an international level through cooperative efforts.

CHAPTER IX

CONCLUSION: FINAL DISCUSSION AND FUTURE DIRECTIONS

Conclusions and Recommendations for Continued Research

The data analysis presented in this dissertation was intended to build upon the studies undertaken that have explored the impacts of vessel noise on marine mammals. This study moves the science community one step closer to understanding the extent to which vessel noise effect one specific whale species, sperm whale, in one isolated area, the Mississippi-Louisiana Shelf region of the GoM. As with Like the preceding studies, however, the conclusions can be applied on a much wider scale and the questions unanswered by this study provide the platform and direction for future research. One such project would be a focused study of the impacts of vessel traffic on sperm whales in the GoM: Because of the opportunistic data collection on which the current project is based, significant auxiliary data are needed in order to assess the impacts of noise on the ecology of the GoM, particularly where behavioral impacts are concerned.

Recommendations for any future focus study include five interlinked data collection methods. The first requirement is a deployment of a buoy or network of buoys in the same area for a time period that overlaps with the original calendar dates of deployment. In order for the data to be comparable, it needs to be collected during the same time of year. The second piece of necessary information is the Automatic Information Systems

(AIS) data from ships passing over the buoys. These data were not included in the current analysis because AIS data was not available until 2004. This type of ship movement data are critical: Not only does AIS data provide vessel size and type, they can also provide ship speed and direction. These components are important for understanding whether direction and speed of approach have an identifiable effect on behavior; for example, whether vessels moving on-shore or off-shore can be heard from greater distances. If bathymetric stripping prevents noise vessels moving down-slope (offshore) from propagating, it may also explain why decreases in clicks are more pronounced for some ship arrivals than others. The third issue to tackle is calculating source level of sperm whale clicks. As discussed in the amplitude analysis section, source level is difficult to calculate because it is generally back calculated from the received level of the click at the sensor. That received level depends on range and orientation of the whale since their clicks are highly directional. A single sensor is unable to resolve position or range, which is why a network of buoys is suggested. While knowing the range and position relative to the buoy will help resolve source level, it cannot account for orientation, and thus an average of these back calculated source levels would need to be used. The fourth recommendation is to use acoustic tags to determine source level. These tags would provide an idea of the source level for clicks, but might also provide an idea of the received sound level sperm whales experience from passing ships. There are many uncertainties associated with acoustics recorded from tags, but the data would be a significant improvement over the calculations and assumptions made from a single buoy.

Additionally, and independent of the acoustic data, tags would provide dive and change in orientation data. These data could be compared for the same before, during, and after ship passages to see whether any difference in dive behavior were detected. Complimentary to that would be orientation and velocity measurements which would show whether the tagged whales changed their direction and speed relative to the course they were headed and/or the approaching or departing ship. This type of information would help answer the question of whether ship noise is obscuring the clicks or whether whales are leaving the area making their clicks undetectable by the buoy.

The fifth and final component for the focus study would be surface observations. Logistically, this is possibly the most difficult because these observations should be executed from a fixed platform where no additional noise (e.g., ship noise from the research vessel) would be added to the system. This is important for objective observations of whale reactions to approaching vessels. The noise from any research vessel in the area may, inadvertently, cause reactions that could not be separated from those of approaching ships, thus biasing the results. From such a fixed platform, it would be possible to observe surface activity patterns, particularly breathing and resting patterns. While acoustic data may be able to detect clicks when whales are present, it cannot explain where whales go when clicking stops. By looking at surfacing patterns, it may be possible to hypothesize whether cessation of clicks is also correlated with increases in surfacing, length of resting, or changes in dive patterns indicating increased time spent at the surface while vessels pass.

As it stands, the major question remaining from the current study is: why is there a decrease in clicks? The only way to begin to address that question is to understand where the whales are in relation to the buoy before the ship approaches and to monitor where whales are found after the ship passes. By knowing the location of the whales, it is possible to determine what portion of the time the buoy is capable of recording them: for example, if the whales are far from the buoy, the lack of clicks could be due to their being too far to be recorded. If they are within detection distance, another explanation would be required. To determine which scenario is occurring necessitates acoustic and visual observations that can be linked with ship positions. The current data set does not allow for this type of analysis and while recent and future acoustic or visual surveys may capture some of the picture, a focused and dedicated project is really necessary to capture all the interlinked parts.

Future Directions for Vessel Quieting

Although no current regulations for the emissions of noise from ships exist, the need for a cohesive global approach to address the issue is apparent as discussed in the preceding chapters. Several working groups have been convened under a number of international bodies to create suggested limits for noise from vessels (McCarthy, 2001). More recently, these limits have been given numerical values which form the basis for future regulations controlling noise emissions from ships such as those presented in the Marine Strategy Framework Directive discussed previously. These numbers are still in the suggestion stage and require more international support to become actual regulations.

Despite support from scientists and some governing bodies, the real challenge will be large scale implementation of mechanisms to control noise emissions.

In the United States, oceangoing vessels loading and unloading cargo at seaports move 99.4% of overseas trade by volume (Nagle, 2011); globally, between 80-90% of international trade travels via waterways (Carmel, 2011). There are 62,000 class A-vessels currently outfitted with AIS tracking devices. From a subset sampled (20,000; Eiden and Martinsen, 2010), at any given time, 75% of that global fleet will be underway. Of those, the median age of U.S. ships in foreign trade is 14 years, compared with the Maersk ships international fleet of six years (Carmel, 2011). That means, of those class A-vessels, there are 26,000 ships under any number of flags moving almost 100% of the trade goods in the world that will need to update, sometimes decade-old ships, to implement new quieting technology which would adhere to new management regulations. The difficulties associated with this are monumental, but not impossible to overcome.

The first step to achieving this kind of unified action toward change is assessing the economic impacts of requiring such a change. In this case, determination must be made of whether the technology needed is available to the private sector and whether implementing that technology is economically feasible for companies and private holders to undertake. This is important because until an international law recognizes and regulates noise as a pollutant, reductions in noise from changes in equipment or ship speed will be voluntary, if at all. Such a law will probably not be forthcoming until the shipping industry itself is aware of the effects of vessel noise perturbations on marine ecosystem inhabitants; is aware of the importance of marine mammals to the marine environment, specifically to the interconnectivity of ecosystems in general; and until the economic costs associated with reduction of vessel noise do not outweigh the environmental benefits or, at least, are feasible.

Applicability of Speed Reductions and Alterations in Shipping Lanes to Noise Reduction

There are some very basic recommendations that, regardless of quieting technology, may reduce noise emissions, or at the very least, reduce the area of exposure for sperm whales in the GoM. The first is to require ships to reduce their speeds as they pass through certain areas. The approach across the Louisiana-Mississippi Shelf cuts through prime sperm whale habitat. As such, recommendations for the reduction of speed to prevent ship collision with whales in the area would not be without precedent. While a non-traditional way to try to manage vessel noise, reductions in speed also generally reduce noise. As discussed in previous chapters, there has been success implementing voluntary areas to be avoided and seasonal management areas where vessel captains show commitment to both speed reduction and more successfully, suggested vessel routes. Because sperm whales in the GoM are not seasonal, time frames for speed restrictions would be more difficult to impose. Instead, a hard look at overlap among shipping lanes and critical habitat and potential alternate routes would be a more practical way to evaluate the efficacy of changes in vessel routes in the GoM.

The preparation for implementing these types of recommendations in the GoM is to first complete a feasibility assessment. To do this, AIS data from as many years as possible should be analyzed to map shipping routes and lanes currently in use, by volume, to see which areas have the most traffic. Then, recommended, voluntary, lanes can be provided to minimize the area where ships are traveling and try to organize traffic separation schemes that efficiently move vessels to port while leaving surrounding areas untraveled – or unperturbed by transiting vessels. In order for this to be successful, cooperation with NOAA and other research groups with sperm whale (and other species) sightings data are necessary to compile density maps showing areas where sperm whales are sighted more frequently and in large groups. Based on these aggregations, shipping lanes can be adjusted to provide a buffer to the area where possible. Concurrently, ship lanes that cross through historically dense areas could be designated as a areas to be avoided (ATBA) with a recommendation to reduce speed below 12 knot and a mandatory speed reduction during times determined to be important for activities like breeding or calving. Until technology is readily available and economically viable to allow implementation of alternative strategies, adjustments in shipping lanes and ship speed are more immediate and more easily implemented mechanisms for reducing vessel noise emissions through reductions in speed as well as streamlining traffic, essentially minimizing zones of impact from vessel traffic.

Final Thoughts

Clearly, stronger measures are necessary for reducing noise perturbations on a global scale. These smaller, first steps of speed reductions and alterations to shipping lanes are potentially feasible and implementation is possible on a shorter time scale since some data are available such as yearly stock reports and U.S. Coast Guard AIS database logs, and other additional, more recent data may exist in unpublished sources. That type of data compilation would be relatively timely and easily distributable to ship owners, ship captains, as well as port authorities through announcements by the U.S. Coast Guard, the National Oceanic and Atmospheric Administration or other similar agency. As technology for ship quieting becomes available and regulations requiring implementation of the newer technology are made, those next steps like retrofitting older vessels and requiring build standards for new vessels can be taken.

The most advantageous and far reaching solution to the noise regulation problem is persuading the IMO to include a further annex to MARPOL that would consider noise a form of pollution and require its management. Continued research into impacts of noise and threshold received levels capable of producing behavioral changes are necessary to advise regulatory measures going forward. These steps are all fundamental in efforts to investigate and address the efficacy of global regulations on noise emissions. It is only through communication among, science, law, and industry personnel that necessary steps can be taken to address the issue successfully.

REFERENCES

Abramson, L., Polefka, S., Hastings, S., and Bor, K. (**2009**). "Reducing the Threat of Ship Strikes on Large Cetaceans in the Santa Barbara Channel Region and Channel Islands National Marine Sanctuary, Recommendations and Case Studies," Channel Islands National Marine Sanctuary Advisory Council, pp. 1-73.

Amundin, M. and Andersen, S. H. (**1983**). "Bony nares air pressure and nasal plug muscle activity during click production in the harbor porpoise, *Phocoena phocoena*, and the bottlenosed dolphin,*Tursiops truncates*," J Exp Biol. **105**, 275–282.

André, M. (**2009**). "The sperm whale sonar, Monitoring and use in mitigation of anthropogenic noise effects in the marine environment," Nuc. Inst. and Meth. in Phys. Res. A **602**, 262-267.

André M., Kamminga, C., and Ketten, D. (**1997**). "Are low frequency sounds a marine hearing hazard: A case study in the Canary Islands," Proc. I.O.A. **19**, 77-84.

Andrew, R. K., Howe, B. M., and Mercer, J. A. (**2002**). "Ocean ambient sound: Comparing the 1960s with the 1990s for a receiver off the California coast," Acoust. Res. Lett. Online. **3**(2), 65-70.

Antunes, R. (**2009**). “Variation in sperm whale (*Physeter macrocephalus*) coda vocalizations and social structure in the North Atlantic Ocean,” Ph.D. dissertation University of St. Andrews, U.K.

Arveson, P. T. and Venditis, D.J. (**2000**). “Radiated noise characteristics of a modern cargo ship,” J. Acoust. Soc. Am. **107**,118–129.

Atapattu, S. (**2002**). “Evolution and status of the precautionary principle in international law,” The Am. Jour. of Int’l. Law, **96** (4), 1016-1018.

Au, W. (**1993**). *The Sonar of Dolphins* (Springer-Verlag, New York).

Au, W. W. L. and Hastings, M. C. (**2008**). *Principles of Marine Bioacoustics* (Springer, New York).

Backus, R.H. & Schevill, W.E. (**1966**). *Physeter Clicks* in *Whales, Dolphins, and Porpoises* edited by K.S. Norris, (University of California Press, Berkeley, CA) pp 510-528.

Barlow, J. and Taylor, B L. (**1998**).” Preliminary abundance of sperm whales in the northeastern temperate Pacific estimated from a combined visual and acoustic survey”. Unpubl. report submitted to Int. Whal. Comm. (SC/50/CAWS/20).

Baumgartner, M. F., Mullin, K.D., May, L. N., and Leming, T. D. (**1999**). *Cetacean Habitats in the Northern Gulf of Mexico* in *The Gulf of Mexico Large Marine Ecosystem, Assessment, Sustainability, and Management* edited by H.Kumpf, K. Steidinger, K. Sherman (Blackwell Science, London).

Beckman, R. (**2007**). "PSSAs and transit passage—Australia's pilotage system in the Torres Strait challenges the IMO and UNCLOS," Ocean Dev. & Int'l. Law, **38**, 325–357.

Best, P. B., Canham, P. A. S., and Macleod, N. (**1984**). "Patterns of reproduction in sperm whales, *Physeter macrocephalus,*" Rep. Int. Whal. Commn. (Special Issue) **6**, 51-79.

Biggs, D.C., Jochens, A. E., Howard, M. K., DiMarco, S. F., Mullin, K. D., Leben, R. R., Muller-Karger, F. E., and Hu, C. (**2005**). "Eddy forced variations in on and off-margin summertime circulation along the 1000m isobaths of the northern Gulf of Mexico, 2000-2003, and links with sperm whale distributions along the middle slope," Circulation in the Gulf of Mexico, Observations and Models. Geophys. Mon. Ser. **161**, 71-85.

Biggs, D.C., Leben, R.R., Ortega-Ortiz, J.G. (**2000**). “Ship and satellite studies of mesoscale circulation and sperm whale habitats in the northeast Gulf of Mexico during GulfCet II,” Gulf Mex. Sci. **18**, 15–22.

Biggs, D.C., and Ressler, P.H. (**2001**). “Distribution and abundance of phytoplankton, zooplankton, ichthyoplankton, and micronekton in the deepwater Gulf of Mexico,” Gulf Mex. Sci. **19**, 7-35.

Bowels, A.E., Smultea, M., Würsig, B., DeMaster, D. P., and Palka, D. (**1994**). “Relative abundance and behavior of marine mammals exposed to transmissions from Heard Island Feasibility Test,” J. Acoust. Soc. Am. **96**, 2469-84.

Caldwell, D., K., Caldwell, M. C., and Rice, D. W. (**1966**). *Behavior of the Sperm Whale, Physeter catodon* in *Whales, Dolphins and Porpoises* edited by K. S. Norris (University of California Press, Berkeley, CA) pp. 677-717.

Carmel, S. M., (**2011**). “Maritime pathways of commerce, ocean shipping and the U.S. flag merchant marine,” U.S Coast Guard Proceedings Summer. http,//www.uscg.mil/proceedings/Summer2011/articles/29_Carmel%20Pathwaysi.pdf

Chapman, D. and Ellis, D. (**1998**). “The elusive decibel, thoughts on sonars and marine mammals,” Can. Acou. **26**(2), 29-31.

Cranford, T. W. (**1999**). “The sperm whale’s nose, sexual selection on a grand scale,” Mar. Mam. Sci. **15**(4), 1133-1157.

Cranford, T. W. (**2000**). *In Search of Impulse Sound Sources in Odontocetes* in, *Hearing in Whales and Dolphins*: *Handbook on Auditory Research* edited by W. W. L. Au, A. N. Popper, and R.R. Fay (Springer, Berlin, Heidelberg, New York), pp. 109–155.

Davis, R.W., Fargion G.S. (Eds.) (**1996**). “Distribution and Abundance of Cetaceans in the North-Central and Western Gulf of Mexico, Final Report. vol. II, Technical Report,” OCS Study MMS 96-0027. Prepared by Texas Institute of Oceanography and National Marine Fisheries Service. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA, pp. 357.

Davis, R.W., Fargion, G.S., May, N., Leming, T.D., Baumgartner, M., Evans, W.E., Hansen, L.J., and Mullin, K.D. (**1998**). “Physical habitat of cetaceans along the continental slope in the north-central and western Gulf of Mexico,” Mar. Mam. Sci., **14**(3), 490-507.

Davis, R.W., Evans, W.E., Würsig, B. (**2000**). “Cetaceans, Sea Turtles and Seabirds in the Northern Gulf of Mexico, Distribution, Abundance and Habitat Associations,” 2, 140 R.W. Davis et al. / Deep-Sea Research I 49 (2002) 121–142 Technical Report. Prepared by Texas A&M University at Galveston and the National Marine Fisheries Service. U.S. Department of the Interior, Geological Survey, Biological Resources Division, USGS/BRD/CR-1999–0006 and Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA, OCS Study MMS 2000–003, pp. 346.

Davis, R.W., Ortega-Ortiz, J. G., Ribic, C. A., Evans, W. E., Biggs, D. C., Ressler, P. H., Cady, R. B., Leben, R. R., Mullin, K. D., Würsig, B. (**2002**). “Cetacean habitat in the northern oceanic Gulf of Mexico,” Deep-Sea Res. I **49**, 121-142.

Dunlop, R. A., Cato, D. H., and Noad, M. J. (**2010**). “Your attention please, increasing ambient noise levels elicits a change in communication behaviour in humpback whales (*Megaptera novaeangliae*),” Proc. R. Soc. B **277** (1693), 2521-2529.

Eiden, G. and Martinsen, T. (**2010**). “Maritime traffic density - results of PASTA MARE project,” Technical Note 4.1 Vessel Density Mapping. Issue 4. Preparatory Action for Assessment of the Capacity of Spaceborne Automatic Identification System Receivers to Support EU Maritime Policy.

Engelhaupt, D., Hoelzel, A. R., Nicholson, C., Frantzis, A., Mesnick, S., Gero, S., Whitehead, H., Rendell, L., Miller, P., De Stefanis, R., Cañadas, A., Airoldi, S., and Mignucci-Giannoni, A. A. (**2009**). "Female philopatry in coastal basins and male dispersion across the North Atlantic in a highly mobile marine species, the sperm whale (*Physeter macrocephalus*)," Mol. Ecol. **18**, 4193-4205.

Foote, A. D., Osborne. R. W., and Hoelzel, A. R. (**2004**). "Environment: Whale-call response to masking boat noise," Nature **428**, 910.

Gales, M. Hindell, and Kirkwood, R. (Eds.) (**2003**). *Marine Mammals Fisheries, Tourism, and Management Issues* (CSIRO Publishing, Collingwood, Australia).

Gero, S., Gordon, J., Carlson, C., Evans, P., and Whitehead, H. (**2007**). "Population estimate and inter-island movement of sperm whales, *Physeter macrocephalus*,in the Eastern Caribbean Sea," J. Cetacean Res. Manage. **9**(2), 143-150.

Goold, J.C. (**1999**). "Behavioural and acoustic observations of sperm whales in Scapa Flow, Orkney Islands," J. Mar. Biol. Assoc. U.K. **79**, 541–550.

Goold, J. C. and Jones, S. E. (**1995**). "Time and frequency domain characteristics of sperm whale clicks," J. Acoust. Soc. Am. **98**, 1279–1291.

Gordon, J. (**1987**). “Behavior and ecology of sperm whales of Sri Lanka,” Ph.D. dissertation, University of Cambridge, Cambridge U.K.

Gordon, J. (**1991**). “Evaluation of a method for determining the length of sperm whales (*Physeter catodon*) from their vocalizations,” J. Zoo. **224**(2), 301–314.

Gordon, J., Rendell, L., Antunes, R., Jaquet, N., Richter, C., and Würsig, B. (**2008**). “Analysis of codas from the Gulf of Mexico and implications for management,” pp. 201-213. *In,* Jochens, A., D. Biggs, K. Benoit-Bird, D. Engelhaupt, J. Gordon, C. Hu, N. Jaquet, M. Johnson, R. Leben, B. Mate, P. Miller, J. Ortega-Ortiz, A. Thode, P. Tyack and B Würsig. Sperm whale seismic study in the Gulf of Mexico, Synthesis report. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2008-006, pp. 341.

Griffin, R.B. (**1999**). “Sperm whale distributions and community ecology associated with a warm-core ring off Georges Bank,” Mar. Mam. Sci. **15**, 33–51.

Grimes, C., B. (**2001**). “Fishery production and the Mississippi River discharge,” Fisheries **26** (8), 17-26.

Grimes, C.B., Finucane, J.H., (**1991**). "Spatial distribution and abundance of larval and juvenile fish, chlorophyll and macrozooplankton around the Mississippi River discharge plume, and the role of the plume in fish recruitment," Mar. Ecol., Prog. Ser. **75**, 109–119.

Gulland, J.A. (**1974**). *Distribution and Abundance of Whales in Relation to Basic Productivity* in *The Whale Problem* edited by W. E. Schevell (Harvard University Press, Cambridge, MA), pp. 27-52.

Hamilton, P. (**1992**). "Lower continental slope cyclonic eddies in the central Gulf of Mexico," J. Geophys. Res., **97**(C2), 2185-2200.

Hamilton, P. and Lee, T. N. (**2005**). "Eddies and jets over the slope of the northeast Gulf of Mexico," Circulation in the Gulf of Mexico, Observations and Models. Geophys. Mono. Ser. **161**, 123-142

Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K., Veirs, S. (**2009**). "Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise," J. Acoust. Soc. Am. **125**, EL27–EL32.

Hopkins, T. L. (**1982**). "The vertical distribution of zooplankton in the eastern Gulf of Mexico," Deep-Sea Research **29**(9A), 1069-1083.

Inkelas, D (**2005**). “Note: Security, sound, and cetaceans, legal challenges to low frequency active sonar under U.S. and international environmental law,” Geo Wash. Int’l. Rev. **37**, 207.

Jaquet, N. (**2006**). “A simple photogrammetric technique to measure sperm whales at sea,” Mar. Mam. Sci. **22**(4), 862-879.

Jaquet, N. and Gendron, D. (**2009**). “The social organization of sperm whales in the Gulf of California and comparisons with other populations,” J. Mar. Biol. Assoc. U.K. **89**(5), 975-983.

Jaquet, N., Dawson, S., and Douglas, L. (**2001**). “Vocal behavior of male sperm whales, why do they click?” J. Acoust. Soc. Am. **109**, 2254–2259.

Jaquet N. and Whitehead, H. (**1996**). “Scale-dependent correlation of sperm whale distribution with environmental features and productivity in the South Pacific,” Mar Ecol. Prog. Ser. **135**, 1-9.

Jaquet, N., Whitehead, H., and Lewis, M. (**1996**).” Coherence between 19th century sperm whale distribution and satellite- derived pigments in the tropical pacific,” Mar. Eco. Prog. Ser. **145**, 1-10.

Jasny, M., Reynolds, J., Horowitz, C., and Wetzler, A. (**2005**) *Sounding the Depths II: The Rising Toll of Sonar, Shipping and Industrial Ocean Noise on Marine Life*. (Natural Resource Defense Council, Washington, D.C.).

Jensen, F.H., Bejder, L., Wahlberg, M., Aquilar Soto, N., Johnson, M., and Madsen, P.T. (**2009**). "Vessel noise effects on delphinid communication," Mar. Ecol. Prog. Ser. **395**, 161-175.

Jochens, A., Biggs, D., Benoit-Bird, K., Engelhaupt, D., Gordon, J., Hu, C., Jaquet, N., Johnson, M., Leben, R., Mate, B., Miller, P., Ortega-Ortiz, J., Thode, A., Tyack, P., and Würsig, B. (**2008**). "Sperm whale seismic study in the Gulf of Mexico, Synthesis report," U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2008-006. pp 341.

Lagueux, K.M., Zani, M. A., Knowlton, A. R., and Kraus S.D. (**2011**). "Response by vessel operators to protection for right whales *Eubalaena glacialis* in the southeast U.S. calving ground," Endang. Species. Res. **14**, 69–77.

Lane, H. and Tranel, B. (**1971**). "The Lombard sign and the role of hearing in speech," J. Speech Hear. Res. **14**(4), 677–709.

Leatherwood, S. and Reeves, R. R. (**1983**). *The Sierra Club Handbook of Whales and Dolphins* (Sierra Club Books, San Francisco, CA).

Leben, R.R. (**2005**). “Altimeter-derived Loop Current metrics,” Circulation in the Gulf of Mexico, Observations and Models, Geophys. Mono. Ser, **161**, 181-201.

Levenson, C. (**1974**). “Source level and bistatic target strength of the sperm whale (*Physeter catodon*) measured from an oceanographic aircraft,” J. Acoust. Soc. Am. **55**, 1100–1103.

Lohrenz, S.E., Dagg, M.J., Whitledge, T.E. (**1990**). “Enhanced primary production at the plume/oceanic interface of the Mississippi River,” Cont. Shelf Res. **10**, 639–664.

Lohrenz, S.E., Fahnenstiel, G.L., Redalje, D.G., Lang, G.A., Dagg, M.J., Whitledge, T.E., Dortch, Q. (**1999**). “Nutrients, irradiance, and mixing as factors regulating primary production in coast waster impacted by the Mississippi River plume,” Cont. Shelf. Res. **19**, 1113– 1141.

Lopatka, M., Adam, O., Laplanche, C., Motsch, J. F., and Zarzycki, J. (**2006**). “Sperm whale click analysis using a recursive time-variant lattice filter,” Appl. Acoust. **67**, 1118–1133.

Lowery, G.H., Jr. (**1974**). *The Mammals of Louisiana and its Adjacent Waters* (Louisiana State University Press, Baton Rouge, LA).

Madsen, P. T., Carder, D. A., Au, W. W. L., Nachtigall, P. E., Møhl, B., and Ridgway, S. H. (**2003**). “Sound production in neonate sperm whale,” J.Acoust. Soc. Am. **113**, 2988–2991.

Madsen PT, Payne R, Kristiansen NU, Wahlberg M, Kerr I,Møhl B. (**2002b**). “Sperm whale sound production studied with ultrasound time/depth-recording tags,” J. Exp. Biol. **205**, 1899–1906.

Madsen, P.T., Wahlberg, M. and Møhl, B. (**2002a**). “Male sperm whale (*Physeter macrocephalus*) acoustics in a high-latitude habitat, implications for echolocation and communication,” Beh. Eco. Socio., **53**, 31–41.

Mate, B. R., Stafford, K. M., Llungblad, D. K., (**1994**). “A change in sperm whale (*Physeter macrocephalus*) distribution correlated to seismic surveys in the Gulf of Mexico,” J. Acoust. Soc. Am. **965**, 3268-69.

Mathias D, Thode A, Straley J, Folkert K. (**2009**). “Relationship between sperm whale (*Physeter macrocephalus*) click structure and size derived from video camera images of a depredating whale (sperm whale prey acquisition),” J. Acoust. Soc. Am. **125** (5), 3444-53.

McCall Howard, M. P. (**1999**). “Sperm whales *Physeter macrocephalus* in the Gully, Nova Scotia, population, distribution, and response to seismic surveying,” B.Sc. Honors Thesis, Dalhousie University, Halifax, Nova Scotia.

McCarthy, E.M. (**2001**). “International regulation of trans-boundary pollutants, the emerging challenge of ocean noise,” Ocean Coastal L. J. **6**, 257-292.

McCarthy, E. (**2004**). *International Regulation of Underwater Sound, Establishing Rules and Standards to Address Ocean Noise Pollution* (Kluwer Academic Publishers, Norwell, MA).

McCarthy, E. and Lichtman, F. (**2007**). “The origin and evolution of ocean noise regulation under the U.S. Marine Mammal Protection Act,” Ocean and Coastal L. J. **13,** 1-46.

McDonald, M. A., Hildebrand, J. A., and Wiggins, S.M. (**2006**). “Increases in deep ocean ambient noise in the northeast Pacific west of San Nicolas Island, California,” J. Acoust. Soc. Am. **120** (2), 711-718.

Miksis-Olds, J. L. and Tyack, P.L. (**2009**). “Manatee (*Trichechus manatus*) vocalization usage in relation to environmental noise levels,” J. Acoust. Soc. Am. **125**(3), 1806-1815.

Miller, P. J. O., Biasson, N., Samuels, A., and Tyack, P. L. (**2000**). “Whale songs lengthen in response to sonar,” Nature **405**, 903.

Møhl, B. (**2001**). “Sound transmission in the nose of the sperm whale *Physeter catodon*: A postmortem study,” J. Comp. Physiol. A **187**, 335–340.

Møhl, B. and Amundin, M. (**1991**). “Sperm whale clicks, pulse interval in clicks from a 21 m specimen,” PhD Thesis, University of Stockholm.

Møhl, B., Wahlberg, M., Madsen, P. T., Heerfordt, A., and Lund, A. (**2003**). “The monopulsed nature of sperm whale clicks,” J. Acoust. Soc. Am. **114**, 1143–1154.

Møhl, B., Wahlberg, M., Madsen, P. T., Miller, L, A., and Surlykke, A. (**2000**). “Sperm whale clicks, directionality and source level revisited,” J. Acoust. Soc. Am. **107**, 638-48.

Moscrop, A. and Swift, R. (**1999**). “Atlantic Frontier Cetaceans: Recent Research on Distribution, Ecology, and Impacts,” Report to Greenpeace, U.K.

Mullin, K.D., Engelhaupt, D., Cates, C. E., and Barros, N. B. (**2003**). “Sperm whale research in the Gulf of Mexico,” International Whaling Commission Working Paper SC/55/O15. Available from, NMFS, Southeast Fisheries Science Center, P.O. Drawer 1207, Pascagoula, MS 39568.

Mullin, K. D. and Hansen, L. J. (**1999**). *Marine Mammals of the Northern Gulf of Mexico* in *The Gulf of Mexico Large Marine Ecosystem* edited by Kumpf, Herb, K. Steidinger, and K. Sherman (Blackwell Science, London) pp. 269-277.

Mullin, K. D., Hoggard, W., Roden, C.L., Lohoefener, R. R., Rogers, C. M., and Taggart, B. (**1994**). “Cetaceans on the upper continental slope in the north central Gulf of Mexico,” Fish. Bull. **92**, 773–786.

Nagle, k., (**2011**). “America’s seaports promote prosperity,” U.S Coast Guard Proceedings Summer.
http,//www.uscg.mil/proceedings/Summer2011/articles/29_Carmel%20Pathwaysi.pdf

National Research Council (**1994**). *Low-Frequency Sound and Marine Mammals, Current Knowledge and Research Needs* (The National Academies Press. Washington, D.C.).

National Research Council (**2003**). *Ocean Noise and Marine Mammals* (National Academy of Sciences, Washington, D.C.).

Newcomb, J., Snyder, M., Hillstrom, W., and Goodman, R. (**2007**). "Measurements of ambient noise during extreme wind conditions in the Gulf of Mexico," Oceans 2007 MTS/IEEE Proceedings.

No Seismic Tests at Twelve Apostles, October 17, (**2003)** http,//www.theage.com.au/articles/2003/10/16/1065917549657.html

Norris, K.S., and Harvey, G.W. (**1972**). "A theory for the function of the spermaceti organ of the sperm whale (*Physeter catodon* L)," Animal Orientation and Navigation. NASA SP-262, S. R. Galler, pp. 397-417.

Notarbartolo di Sciara, N. (**2002**). "Cetaceans of the Mediterranean and Black Seas: State of Knowledge and Conservations Strategies," A report to the ACCOBAMS Secretariat, Monaco.

O’Hern, J. E., and Biggs, D.C. (**2009**). “Sperm whale (*Physeter macrocephalus*) habitat in the Gulf of Mexico, Satellite Observed ocean color and altimetry applied to small scale variability in distribution,” Aqua. Mam. **35**, 358-366.

Okeanos, Foundation for the Sea (**2008**). “Underwater Radiated Noise of Ocean-Going Merchant Ships,” International Workshop on Shipping Noise and Marine Mammals. Hamburg, Germany, 21st-24th April.

Parks, S. E. and Clark, C. W. (**2007**). “Short- and long-term changes in right whale calling behavior, the potential effects of noise on acoustic communication,” J. Acoust. Soc. Am. **122** (6), 3725-3731.

Parks, S., Johnson, M., Nowacek, D., and Tyack, P. (**2011**). “Individual right whales call louder in increased environmental noise,” Biol. Lett. **7**(1), 33-35.

Parks, S.E., Urazghildiiev, I., Clark, C.W. (**2009**). “Variability in ambient noise levels and call parameters of North Atlantic right whales in three habitat areas,” J. Acoust. Soc. Of Am. **125**(2), 1230-1239.

Perrin, W.F., Würsig, B. and Thewissen, J.G.M. (**2008**). *Encyclopedia of Marine Mammals* (Academic Press, San Diego, CA).

Pierce, A. (**1983**). *Acoustics*: *An Introduction to its Physical Principles and Applications* (Acoustical Society of America, Melville, NY).

Port Authority of New Orleans, Louisiana, USA (**2009**). http,//www.portno.com/pno_pages/about_overview.htm

Port of Houston Authority, Texas, USA (**2009**). http,//www.portofhouston.com/geninfo/overview1.html

Port of Louisiana, Louisiana, USA (**2011**). http://portsoflouisiana.org/documents/port_profiles/New_Orleans.pdf

Protocol on Environmental Protection to the Antarctic Treaty (**1991**) Article 3, Environmental Principles. http,//www.antarctica.ac.uk/about_antarctica/geopolitical/treaty/update_1991.php accessed Sept 2011.

Reeves, R. R., Lund, J. N., Smith, T. D., and Josephson, E. A. (**2011**). "Insights from whaling logbooks on whales, dolphins, and whaling in the Gulf of Mexico," Gulf Mex. Sci. **1**, 41-67.

Rendell, L. and Whitehead, H. (**2001**). “Culture in whales and dolphins,” Behav. Brain. Sci. **24**, 309- 82.

Rendell, L. and Whitehead, H. (**2003**). “Vocal clans in sperm whales (*Physeter macrocephalus*),” Proc. Roy. Soc. London B **270**, 225-31.

Ressler, P.H., and Jochens, A. E. (**2003**). “Hydrographic and acoustic evidence for enhanced plankton stocks in a small cyclone in the northeastern Gulf of Mexico,” Cont. Shelf Res. **23**(1), 41–61.

Rhinelander, M. and Dawson, S. (**2004**). “Measuring sperm whales from their clicks: Stability of inter pulse intervals and validation that they indicate whale length,” J. Acoust. Soc. Am. **115** (4).

Rice, D.W. (**1989**). *Sperm Whale, Physeter macrocephalus Linnaeus, 1758* in *Handbook of Marine Mammals* (Academic Press, London) pp. 177- 233.

Richardson, W. J., Greene, C.H. Jr., Malme, C. I. and Thomson, D. H. (**1995**). *Marine Mammals and Noise* (The Academic Press, San Diego, California).

Richter, C., Gordon J., Jaquet, N., and Würsig, B. (**2008**). “Social structure of sperm whales in the northern Gulf of Mexico,” Gulf Mex. Sci. **26**(2), 118-123.

Ridgway S. H., and Carder, D. A. (**1988**). *Nasal Pressure and Sound Production in an Echolocating White Whale, Delphinapterus leucas* in *Animal Sonar Systems, Processes and Performance* edited by P.E. Nachtigall and P. W. B. Moore (Plenum Press, New York) pp. 53–60.

Ridgway, S. H., and Carder, D. A. (**2001**). “Assessing hearing and sound production in cetacean species not available for behavioral audiograms, experience with *Physeter, Kogia,* and *Eschrichtius*,” Aquat. Mam. **27**, 267–276.

Riley, G. A. (**1937**). “The significance of the Mississippi River drainage for biological conditions in the northern Gulf of Mexico,” J. Marine Rcs. **1**, 60-74.

Rovaniemi Declaration in Declaration on the Protection of the Arctic Environment 1991. http,//arctic-council.org/section/documentation. Accesses Sept 2011

Scheifele, P.M., Andrew, S., Cooper, R. A., Darre, M., Musiek F. E. and Max, L. (**2005**). “Indication of a Lombard vocal response in the St. Lawrence River beluga,” J. Acoust. Soc. Am. **117** (3).

Soto, A., Johnson, N., Madsen, M., Tyack, P. T., Bocconcelli, A. and Borsani, J. F. (**2006**). “Does intense ship noise disrupt foraging in deep-diving Cuvier's beaked whales (Ziphius cavirostris),” Mar. Mamm. Sci. **22**, 690 -699.

Southall, B. (**2004**). “Shipping Noise and Marine Mammals, A Forum for Science, Management and Technology,” Final report for NOAA international symposium. http,//www.nmfs.noaa.gov/pr/pdfs/acoustics/shipping_noise.pdf

Sturges, W. and Leben, R. (**2000**). “Frequency of ring separation from the Loop Current in the Gulf of Mexico, A revised estimate,” J. Physi. Oceano. **30**, 1814-1819.

Tasker, M. L., Amundin, M., André, M., Hawkins, A., Lang, W., Merck, T., Scholik-Schlomer, A., Teilmann, J., Thomsen, F., Werner, S., and Zakharia, M. (**2010**). “Report: Underwater noise and other forms of energy,” Marine Strategy Framework Directive Task Group 11 Prepared under the Administrative Arrangement between JRC and DG ENV (no 31210 – 2009/2010), the Memorandum of Understanding between the European Commission.

Thode, A., Millinger. D., Stienessen, S., Martinez, A., Mullin, K. (**2002**). “Depth-dependant acoustic features of diving sperm whales (*Physeter macrocephalus*) in the Gulf of Mexico,” J. Acoust. Soc. Am. **112** (1), 308-321.

Thompson, M. A, Cabe, B., Pace, R. M., Levenson, J., and Wiley, D. (**2011**). “Vessel compliance and commitment with speed reduction regulations in the U.S. Cape Cod Bay and off Race Point right whale seasonal management areas,” Proceedings of the 2011 Biennial Meeting of the Society for Marine Mammalogy.

Townsend, C.H. (**1935**). “The distribution of certain whales as shown by logbook records of American whale ships,” Zoologica **19**, 1-50.

“Trail Smelter Arbitration (U.S. v Can),” 3 U.N. Rep. Awards 1905, 1965 (**1941**), reprinted in **35** Am J. Int’l L. (1941), 684-734.

United Nations (**1992**). “Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas,” March 17, 1992. http://www.ascobans.org/pdf/Ch_XXVII_09_CertifiedTrueCopiesAgreement.pdf

Urick, R. (**1983**). *Principles of Underwater Sound, 3rd ed*. (Mcgraw-Hill. New York).

U.S. EPA (**2011**). “Gulf of Mexico Facts,” http,//www.epa.gov/gmpo/about/facts.html

Vanderlaan, A. S. M. and Taggart, C. T. (**2009**). “Efficacy of a voluntary area to be avoided to reduce risk of lethal vessel strikes to endangered whales,” Cons. Bio., **23**(6), 1467–1474.

Von Zharen, W. M. (**1996**). *ISO 14001, Positioning Your Organization for Environmental Success* (ABS Consulting, Government Institutes, Rockville Maryland).

Wade, P.R. and Angliss, R. P. (**1997**). “Guidelines for Assessing Marine Mammal Stocks, Report of the GAMMS Workshop,” April 3-5, 1996, Seattle, Washington. NOAA Tech. Memo. NMFS-OPR-12.

Watkins, W. A. (**1980**). *Acoustics and the Behavior of Sperm Whales* in *Animal Sonar Systems*, edited by R. Busnel and J. F. Fish (Plenum Press, New York) pp 291-97.

Waring, G.T., Fairfield, C.P., Ruhsam, C.M., and Sano, M. (**1993**). “Sperm whales associated with Gulf Stream features off the northeastern U.S.A. shelf,” Fish. Oceano. **2**, 101–105.

Watkins, W. A. and Schevill, W.E. (**1977**). “Sperm whale codas,” J. Acoust. Soc. Am. **62**, 1486-1490.

Waring, G. T., Hamazaki, T., Sheehan, D., Wood, G., and Baker, S. (**2001**). **“**Characterization of beaked whales (*Ziphiidae*) and sperm whale (*Physeter macrocephalus*) summer habitat in shelf-edge and deeper waters off the northeast,” U. S. Mar. Mam. Sci., **17** (4), 703–717.

Waring, G. T., Josephson, E., Maze-Foley, K., Rosel, P. E., editors. (**2011**). “U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments – 2010,” NOAA Tech

Memo NMFS NE 219; 598 p. Available from, National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026.

Weilgart, L.S. (**1990**). “Vocalizations of the sperm whale (*Physeter macrocephalus*) off the Galapagos Islands and related to behavioral and circumstantial variables,” Ph.D. dissertation, Dalhousie University, Halifax, Nova Scotia.

Weilgart, L. S. and Whitehead, H. (**1988**). “Distinctive vocalizations from mature sperm whales (*Physeter macrocephalus*),” Can J. Zool **66**, 1931-37.

Weilgart, L. and Whitehead, H. (**1997**) “Group-specific dialects and geographical variation in coda repertoire in South Pacific sperm whales,” Behav. Ecol. Sociobiol. **40**, 277-285.

Welsh, S. E. and Inoue, M. (**2000**). “Loop current rings and the deep circulation in the Gulf of Mexico,” J. Geophys. Re. **105**, 16, 951-16,959.

Whitehead, H. (**1993**). “The behaviour of mature male sperm whales on the Galapagos breeding grounds,” Can. J. Zool. **71**, 689–699.

Whitehead, H. (**1996**) “Babysitting, dive synchrony, and indications of alloparental care in sperm whales,” Behav. Ecol. Sociobiol. **38**, 237-244.

Whitehead, H. (**2002**). “Estimates of the current global population size and historical trajectory for sperm whales,” Mar. Ecol. Prog. Ser. **242**, 295-304.

Whitehead, H. (**2003**). *Sperm Whales, Social Evolution in the Ocean* (University of Chicago Press, Chicago, IL.)

Whitehead, H. and Weilgart, L. (**1991**). “Patterns of visually observable behaviour and vocalizations in groups of female sperm whales,” Behaviour **118**, 275-296.

Wiseman, W.J., Jr., and Sturges, W. (**1999**). *Physical Oceanography of the Gulf of Mexico: Processes that Regulate its Biology* in *The Gulf of Mexico Large Marine Ecosystem* edited by H. Kumpf, K. Steidinger, K., and K. Sherman (Blackwell Science, Inc., Malden, MA) pp. 77- 92.

Wormuth, J.H., Ressler, P.H., Cady, R.B, Harris, E.J., (**2000**). “Zooplankton and micronekton in cyclones and anticyclones in the northeast Gulf of Mexico,” Gulf Mex. Sci. **18**, 23–34.

Worthington, L. V. and Schevill W. E. (**1957**). “Underwater sounds heard from sperm whales,” Nature **180**, 291.

Würsig, B., Jefferson, T., and Schmidly, D. (**2000**). *The Marine Mammals of the Gulf of Mexico* (Texas A&M University Press, College Station).

Yaggi, M. (**1996**) “United States v. Hayashi, Taking aim at the Marine Mammal Protection Act,” Pace Envtl. L. Rev. **14**, 409.

Zimmer, W., Tyack, P., Johnson, M., and Madsen, P. (**2005**). “Three-dimensional beam pattern of regular sperm whale clicks confirms bent-horn hypothesis,” J. Acoust. Soc. Am. **117**(3), 1474-1485.

VITA

Alyson Julie Azzara completed her undergraduate Bachelor of Arts in Biology from Temple University in 2004 with a double minor in Environmental Studies and Spanish. She attended Texas A&M University for her Master's of Science degree in Oceanography, which she finished in 2006. Ms. Azzara then worked as a contractor for marine mammal research, participating in 16 deep sea research cruises for a total of more than 300 days at sea. Her dissertation focuses on the impacts of anthropogenic noise from shipping on marine mammals and the marine environment. She is now working at the Department of Transportation as a Knauss Marine Policy Fellow using her academic expertise as a Policy advisor for a cabinet level committee.

For any questions regarding this dissertation Ms. Azzara can be reached by:

Mail at:

Committee on the Marine Transportation System

Office of the Executive Secretariat

U.S. Department of Transportation

1200 New Jersey Ave SE

Washington, DC 20590

Electronically at: aly.azzara@gmail.com